Numerical simulation of dividing wall column with vapor recompression located at side product stage

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Abstract: The energy efficiency of dividing wall column (DWC) can be further improved by the vapor recompression (VRC), but large temperature difference between overhead and bottom of the DWC hindered their combination. Meanwhile, it is difficult to choose suitable side heat exchanger position in the DWC. In this paper, we provided a direct method to design the configurations that the VRC assisted DWC at the side product stage. The Column Grand Composite Curve (CGCC) profiles were used to determine the type of phase withdrawn from the side product stage. In the CGCC profiles, if the side product stage was located in the side reboiler region, the vapor should be withdrawn from the side product stage, the SCVRC-DWC and IR-SRVRC-DWC configurations can be achieved. If the side product stage was located in the side condenser region, the liquid should be withdrawn from the side product stage, the SRVRC-DWC and the IC-SRVRC-DWC configuration can be

achieved. Three separation cases with different ESI values were simulated and the results inferred that the proposed configurations had high energy efficiency when enough vapor or liquid flow can be withdrawn from the side product stage.

Keywords: Dividing wall column, Vapor recompression, CGCC

1. Introduction

Distillation is the most widely applied separation unit in chemical industries, but it has low thermodynamic efficiency and large energy consumption. Therefore, the development of highly energy saving column configuration would bring great benefits to overall chemical industries.

As an intensified thermally coupled system, dividing wall column (DWC) had high energy efficiency and low equipment cost.^[1-3] The optimization design and controllability of DWC had been researched intensively.^[4-9] In a typical DWC configuration, all heat was input at the bottom reboiler and removed from the top condenser. So the reboiler and condenser duties were always larger than the single conventional column.^[10-12] It meant that significant waste heat of DWC could be recovered. Vapor recompression (VRC) was considered as the simplest external heat integrated technology for distillation. Some studies^[13-16] found that the VRC was most beneficial for separating close boiling mixture with high heat loads and small column pressure drops.

The VRC assisted DWC configurations had been researched recently, Rangaiah^[17] investigated the configurations that the VRC installed between the overhead and bottom of DWC(named as VRC-DWC) , and found that VRC have significant energy

efficiency with small temperature difference between the overhead and bottom of DWC. But this temperature difference was always larger than the conventional column especially for separating the wide boiling mixtures. Lee^[18] provided the side VRC assisted DWC schemes in which VRC system was located in rectifying section or stripping section. Although the temperature difference between two withdrawn streams is reduced, but the driving force of mass transfer in the VRC added stage will be decreased. ^[19, 20]

We focus our research on the configurations that the VRC was installed at the side product stage of the DWC. Compared with other side VRC assisted DWC configurations, this kind of configuration had two outstanding advantages. One was that the addition of VRC can't generate large influence to the separation because the stream withdrawn from the side product stage was purer than other side stream. Another one was that the temperature of the stream withdrawn from side product stage will not be changed largely after exchanged heat, which was very beneficial to the heat transfer.

It was necessary to develop more direct method to design the DWC with VRC located at the side product stage. For the DWC, either side reboiler or side condenser could be installed at the side product stage, because it was the connection of the stripping and rectifying sections of the DWC. But only one type of side exchanger can improve its energy efficiency. Navarro-Amoros^[21] found that excess vapor or liquid will be arose at the side product stage when the DWC was considered as three columns model, so the VRC or the reverse vapor recompression (RVRC) could be

installed at the side product stage. But the excess vapor or liquid was justly achieved in optimal three columns model, the RVRC system wasn't commonly used in industry.

In this article, we provided a new method to design the DWC with VRC located at the side product stage. In the method, the Column Grand Composite Curve (CGCC) profiles were used to determine the type of phase withdrawn from the side product stage. With the aid of CGCC profiles, four kinds of VRC assisted DWC configurations were proposed.

2. Dividing wall column with VRC located at the side product stage

If the vapor was withdrawn from the side product stage, two kinds of VRC assisted DWC configurations could be achieved, Fig.1 (a) shown that the VRC was between the side product stage and the bottom reboiler, which was equivalent to the VRC assisted DWC with a side condenser. So this type of configuration can be named as SCVRC-DWC. To further reduce the temperature difference between two withdrawn streams, the liquid stream could be withdrawn from the stripping section. So the SCVRC-DWC with an intermediate reboiler (IR) configuration could be achieved and named as IR-SCVRC-DWC shown in Fig.1 (b)

If the liquid was withdrawn from the side product stage, two kinds of VRC assisted DWC configurations could be achieved. Fig.1(c) shown the configuration that the VRC was between the overhead and the side product stage, which was equivalent to the VRC assisted DWC with a side reboiler and can be named as SRVRC-DWC. To further reduce the temperature difference between two withdrawn streams, the vapor

stream can be withdrawn from the rectifying section. So the SRVRC-DWC with an intermediate condenser (IC) configuration could be achieved and named as IC-SRVRC-DWC shown in Fig.1 (d).

3. Method to determine the type of VRC assisted DWC configurations

CGCC profiles were referred to the temperature-enthalpy (T-H) and stage-enthalpy (S-H) profiles of the distillation column, they illustrated the heat loads of side reboiler or side condenser in each stage for the thermodynamically reversible column. In S-H profile, the ideal enthalpies were calculated for a given stage of column by assuming that the equilibrium and operating lines coincide at each stage. So it can be used to identify the best position of side condenser or side reboiler.^[22-24] Fig.2 shown the S-H profile of a conventional column for binary mixture separation, in which the region between the ideal and actual enthalpy profiles was dividing into two parts by the pinch point, the above part was the side reboiler region and the below part was the side condenser region.

For the DWC configuration, the CGCC profile of the main column could also be achieved.^[25] If the side product stage was in the side condenser region, from which the vapor could be withdrawn, and then the SCVRC-DWC and IR-SCVRC-DWC configurations could be achieved. If the side product stage was in the side reboiler region, from which the liquid could be withdrawn, and then the SRVRC-DWC and IC-SRVRC-DWC configurations were achieved.

4. Design basis and methodology

4.1 Design of optimal DWC

The temperature distribution along the column had significant influence to the VRC installation. So the ternary mixture for DWC simulation was chosen according to the values of the ease of separability index (ESI) (defined by Tedder and Rudd^[26]), which roughly reflected the column temperature distribution. For a ternary mixture where A, B, C represented the light, middle and heavy component respectively, ESI equaled to α_{AB}/α_{BC} . If $ESI < 1$, the A/B separation was harder than the B/C separation, so the temperature difference between the overhead and the side product stage is lower than that between the side product stage and the bottom. If $ESI > 1$, the A/B separation was easier than the B/C separation, so the temperature difference between the overhead and the side product stage is higher than that between the side product stage and the bottom. Three ternary mixtures with representative ESI values were chosen, which were (1) *n*-pentane, *n*-hexane, *n*-heptane mixture (2) *i*-pentane, *n*-pentane, *n*-hexane mixture and (3) *n*-butane, *i*-pentane, *n*-pentane mixture. Their ESI values were 1.04, 0.47 and 1.86 respectively and represented the $ESI=1$, $ESI < 1$ and $ESI > 1$ mixtures.^[27]

The feed conditions and product specifications for three cases were listed in Table 1, where $x_{A,D}$, $x_{B,S}$ and $x_{C,W}$ represented the key component compositions in distillate(D), side product(S) and bottom product(W) respectively. The equal-mole feed was adopted in our work because DWC generally had the high energy efficiency under this feed condition. The design pressure for each case was chosen to ensure the use of cooling water in the condensers.

Fig.3 (a) shown the structure of the DWC, N_{T1} and N_{T2} represented the stage number of the main column and the prefractionator respectively. N_F , N_S , N_L and N_V

represented the feed stage, side product stage, liquid and vapor connection stages respectively. These structure variables were firstly calculated by shortcut method based on the Fenske-Underwood-Gilliland-Kirkbride equations. Then the rigorous simulation was performed by Aspen Plus V7.3TM. The Soave-Redlich-Kwong (SRK) equation was chosen to predict the thermodynamic property in three cases. This model was usually recommended for the petrochemical application, the missing binary parameters were estimated by UNIFAC model. Two RadFrac models were used to simulate the prefractionator and the main column as shown in Fig.3 (b), where L_1 , V_1 , L_2 , V_2 represented their connection streams.

Optimal design of DWC was to determine both structural and operating variables in order to minimize total annual cost (TAC). Theoretically, the DWC had five independent structural variables including N_{T1} , N_{T2} , N_F , N_S and N_L (or N_V). A steady state DWC had five independent operating variables including the liquid split ratio (r_L) and vapor split ratio (r_V) to the prefractionator, the reflux rate (R), the side product rate (S) and the distillate product rate (D).^[28,29] R , S and D get fixed by product purity constraints on the distillate, side product, and bottoms product streams. The remaining variables, r_L and r_V were the unconstrained operating variables and can be used to get the minimum reboiler duty. In simulation, the values of r_L and r_V can't be regulated directly, so the flowrates of connecting streams (V_1 and L_2) were chosen as the vary parameters to optimized the reboiler duty. Sequential iterative optimization procedure were performed and shown in Fig.4.

4.2 Design and optimization of VRC assisted DWC configurations

The VRC assisted DWC configurations were simulated with aid of S-H profile. The Column Targeting Thermal Analysis^[30] in Aspen Plus can generate the S-H profile based on the Practical Near-Minimum Thermodynamic Condition (PNMTC) Approximation.^[22] In the simulation, the option “include column targeting thermal analysis” must be selected.

In these configurations, the compression ratio (CR) should be regulated to make the minimum heat transfer temperature difference be 10 °C in the compressed vapor heating reboiler. The vapor stream was preheated by a heater before entering the compressor, and the stream from the throttle valve (TV) was fully condensed by a cooler. The adiabatic efficiency of compressor was set to be 75%.

The stage numbers of all sections were kept consistent before and after introducing the VRC, and the V_1 and L_2 were still chosen as the vary parameters to optimized the reflux ratio in VRC assisted DWC configurations. The flowrate of side withdrawn stream was achieved by sensitivity analysis, and 50% of internal vapor or liquid flowrate was as the initial value. For IR-SCVRC-DWC and IC-SRVRC-DWC configurations, the IR and IC positions were achieved by sensitivity analysis.

4.3 Economic analysis of different configurations

The DWC configurations are evaluated with the total annual cost (TAC) which was the summation of operating cost and annualized capital cost. The operating cost could be calculated by CAPCOST. For the sake of simplicity, operating costs were taken to be identical to utility costs, which were the summation of electricity (16.8 \$/GJ), low pressure steam (13.28 \$/GJ), high pressure steam (14.19 \$/GJ) and cooling water

(0.354 \$/GJ) for a year containing 8322 operating hours.^[31] As we known that the economic results of VRC assisted columns were sensitive to electricity cost, so the economic data of all configurations were recalculated with electricity cost (26.56\$/GJ) as 2 times of the low pressure steam cost.

Capital cost was estimated by summing up the cost of column shell, trays, heat exchangers and compressor. The estimating formulas and parameter values were listed in Table 2^[32, 33] and Marshall and Swift equipment cost index (M&S index) was updated to 1468.6 in 2012.^[5] Because the construction and installation of a DWC might be much more difficult than that of a conventional distillation column, a roughly 50% penalty was assumed when calculating the shell and tray costs of DWC

The annualized capital cost of the DWC configurations was calculated by Eq. (2).

$$\text{Annualized capital cost} = \text{capital cost} \times \frac{i \times (1+i)^n}{(1+i)^n - 1} \quad (2)$$

Where i was the fractional interest rate per year and set by 8%, n was the lifetime of equipment and set by 10 year.^[21]

5. Results and discussions

5.1 Case 1 (ESI=1)

The simulation results of DWC in case 1 were shown in Fig.5 (a). It inferred that the total number of stage of DWC was 46 and side product stage was stage 14. The temperature difference between the overhead and bottom was 64.2°C. In order to provide enough drive force of heat transfer, the compression ratio (CR) was high to 5.9 in the VRC-DWC configuration as shown in Fig.5 (b).

Fig.6 (a) shown that the pinch point of S-H profile for the DWC was located at

stage 32. It meant that the side product stage was in the side condenser region, and vapor stream can be withdrawn from stage 14. Then the SCVRC-DWC and IR-SCVRC-DWC configurations were achieved as shown in Fig.7 (a) and (b).

Fig.7 (a) and (b) shown that the temperature difference between two withdrawn streams was $29.4\text{ }^{\circ}\text{C}$ and $16.3\text{ }^{\circ}\text{C}$ respectively in the SCVRC-DWC and IR-SCVRC-DWC configurations, so their CR values were reduced to 2.70 and 1.95 respectively and large compression duty could be saved. Detailed energy and economic data of the configurations were listed in Table 3. It shown that the TAC savings of three VRC assisted DWC configurations was 0.50%, 4.58% and 8.57% respectively. IR-SCVRC-DWC configuration is the best in the VRC assisted DWC configurations. The cost results under high electricity cost ($26.56\text{\$/GJ}$) shown that the TAC savings of VRC-DWC, SCVRC-DWC and IR-SCVRC-DWC were -14.69%, 2.28% and 6.69% respectively. The energy efficiency of the proposed configurations was more outstanding under higher electricity cost in this case.

Fig.8 (a)~(d) shown the liquid and vapor flow profiles in prefractionator (V_P and L_P) and main column (V_M and L_M) of the DWC before and after the introduction of the VRC. For the prefractionator, L_P and V_P had no significant change after introduction of the VRC. For the main column, V_M and L_M decreased by around 100kmol/h above the side product stage, and increased by around 30kmol/h below the side product stage in the SCVRC-DWC configuration. These changes of vapor and liquid flowrates reflected the influence of side VRC on the column.¹⁷ Fig 8(d) shown that the vapor flowrate at side product stage was around 150kmol/h , and the amount of vapor

withdrawn from this stage can't be large. Therefore, the energy savings of two proposed configurations weren't high enough.

5.2 Case 2(ESI<1)

The simulation results of DWC in case 2 were shown in Fig.9 (a). It inferred that the total number of stage of DWC was 97 and the side product stage was stage 86. The temperature difference between the overhead and bottom was 41.7 °C. Based on the results, the compression ratio was fixed as 3.90 in VRC-DWC configuration shown in Fig.9 (b).

Fig.10 (a) shown that the pinch point of the S-H profile for the DWC was located in stage 41. The side product stage was in the intermediate reboiler region, so the liquid was withdrawn from stage 86 and then the SRVRC-DWC and IC-SRVRC-DWC configurations were achieved and shown in Fig. 11(a) and (b) respectively.

Fig.11(a) and (b) shown that the temperature difference between two withdrawn streams was 7.9 °C and 7.6 °C in the SRVRC-DWC and IC-SCVRC-DWC configurations respectively, so their CR values were reduced to 1.69 and 1.67 respectively and large amount of compressor duties were saved. Table 4 listed the detailed economic data of the configurations. It was shown that the TAC savings of three VRC assisted DWC configurations were 24.40%, 29.49% and 27.61% respectively, the optimal one was SRVRC-DWC. The intermediate condenser was not necessary to add under small temperature difference between two withdrawn streams like that in case 2. The TAC savings were 12.17%, 26.14% and 24.42% respectively in these configurations with high electricity cost. The energy efficiency of the

proposed configurations was more outstanding under higher electricity cost in this case.

Fig.12 (a) ~ (d) showed the liquid and vapor flow profiles of prefractionator and main column of the DWC before and after the introduction of the VRC. The vapor and liquid flowrates in the prefractionator and the main column section between stage 15 and stage 86 were increased after introducing the VRC into the DWC, because large side liquid withdrawn generated internal reflux. The liquid flowrate at the side stage was around 650kmol/h, enough liquid can be withdrawn from this stage, so the operating costs of the proposed configurations reduced significantly in this case.

5.3 case 3 (ESI>1)

The simulation results of DWC in case 3 were shown in Fig.13 (a). It inferred that the side product was withdrawn form stage 15 and the temperature difference between the overhead and the bottom was 41.2 °C. The compression ratio of the VRC-DWC configuration was fixed as 3.2 shown in Fig.13 (b).

Fig.14 (a) shown the pinch point of S-H profile for the DWC was located in stage 61. The side product stage was in the intermediate condenser region, so the vapor stream was withdrawn from stage 15, then the SCVRC-DWC and IR-SCVRC-DWC configurations were achieved and shown in Fig. 15(a) and (b) respectively.

Fig.15 (a) and (b) shown that the temperature differences between the side product stage and the bottom were 8.3 °C and 8.2 °C in SCVRC-DWC and IR-SCVRC-DWC, so their compression ratios were reduced to 1.55 and 1.54 respectively. Table 5 listed the detail economic data of the configurations. It inferred that the TAC savings of

SCVRC-DWC and IR-SCVRC-DWC were up to 40.86% and 40.80% respectively and much higher than that (26.30%) of VRC-DWC configuration, which benefited from the small compression ratio and large side withdrawn flowrate in two configurations. The TAC savings of IR-SCVRC-DWC was not high as SCVRC-DWC, so the addition of intermediate reboiler was not necessary when the temperature difference between two withdrawn streams was small like that in case 3. The TAC savings were 14.79%, 37.77% and 37.74% respectively in VRC-DWC, SCVRC-DWC and IR-SCVRC-DWC configurations under higher electricity cost. It inferred that the energy efficiency of the proposed configurations was more outstanding under high electricity cost in this case.

The liquid and vapor flow profiles of the DWC before and after the introduction of the VRC are shown in Fig.16 (a)~(d). We can see that the vapor and liquid flowrates in the prefractionator and the main column section between stage 15 and stage 107 were increased, but the flowrates at other stages in the main column were decreased. These changes reflected the influence of side VRC on the DWC.

6. Conclusions

In order to improve the energy efficiency of DWC, four kinds of VRC assisted DWC configurations were proposed in this article. In these configurations, the VRC was installed at the side product stage of DWC and the compressor can be worked at small compression ratio. Some conclusions were achieved from three cases with different ESI values as the followings:

(1) S-H profile was effective to determine the type of configurations that VRC assisted

DWC at the side product stage.

(2) The configuration that VRC assisted DWC at the side product stage had significant energy saving capacity when enough vapor or liquid flow can be withdrawn from the side product stage.

(3) The IC-SRVRC-DWC and IR-SCVRC-DWC configurations were not recommended for the narrow boiling mixture separation.

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Figures in the article

Fig.1 Schematic diagram of the (a) SCVRC-DWC, (b) IR-SCVRC-DWC, (c) SRVRC-DWC and (d) IC-SRVRC-DWC

Fig.2 S-H profile of the conventional column

Fig. 3 (a) Schematic diagram of DWC and (b) simulation of DWC

Fig.4 Optimization procedure of the DWC

Fig.6 S-H profile of the DWC in case 1

(a)

(b)

Fig.7 Simulation results of the (a) SCVRC-DWC and (b) IR-SCVRC-DWC in case 1

(a)

(b)

(c)

(d)

Fig. 8 Liquid and vapor flow profiles of the (a), (b) prefractionator and (c), (d) main column of three configurations in case 1

Fig.9 Simulation results of the (a) DWC and (b) VRC-DWC in case 2

Fig.10 S-H profile of the DWC in case 2

(a)

(b)

Fig.11 Simulation results of the (a) SRVRC-DWC and (b) IC-SRVRC-DWC in case 2

(a)

(b)

(c)

(d)

Fig.12 The liquid and vapor flow profiles of (a), (b) the prefractionator and (c), (d) the main column of three configurations in case 2

Fig.14 S-H profile of the DWC in case 3

(a)

(b)

(c)

(d)

Fig.16 The liquid and vapor flow profiles of (a), (b) the prefractionator and (c), (d) the main column of three configurations in case 3

Tables in the article

Table 1. Feed Conditions and Separation Task of Two Cases

Items	values
Feed flowrate (kmol/h)	300
Feed mole fraction(A:B:C)	0.33:0.33:0.34
Feed thermal condition	$q=0$
Design pressure	2 bar in case1 and 2 4.7 bar in case 3
Product mole purity	$x_{A,D}=0.98$, $x_{B,S}=0.96$, $x_{C,W}=0.98$

Table 2. Cost Estimating Formula and Parameter Values³³

(1) Column shell: $\left(\frac{M\&S}{280}\right) \times C \times d_{col}^{1.066} \times h_{col}^{0.802}$ d_{col} is the column diameter, h_{col} is the column height. $M\&S = 1468.6$, and the coefficient $C = 3919.32$
(2) Column tray: $\left(\frac{M\&S}{280}\right) \times 97.243 \times d_{col}^{1.55} \times h_{tray} \times F_C$ h_{tray} is the column height between top and bottom tray. $F_C = c_s + c_t + c_m = 0 + 0 + 1.4 = 1.4$
(3) Heat exchanger: $\left(\frac{M\&S}{280}\right) \times c \times A^{0.65}$ Coefficient $c = 1609.13$ for the Condenser and $c = 1775.26$ for kettle reboiler.
(4) Compressor: $\left(\frac{M\&S}{280}\right) \times 2047.24 \times bp^{0.82}$

Table 3. Comparison of Estimated Capital and Operating Costs in Case 1

Items	DWC	VRC-DWC	SCVRC-DWC	IR-SCVRC-DWC
Condenser duty (KW)	2800	0.0	2141	2153
Cost of cooling water (\$/y)	29700	0.0	22700	22800
Reboiler duty(KW) (steam-heated)	3020	973	2450	2433
Reboiler duty (KW) (compressed vapor-heated)	0.0	2047	688	718
Cost of medium pressure steam (\$/y)	1283900	413600	1041500	1034300
Compressor duty(KW)	0.0	711	108	74
Cost of electricity(\$/y)	0.0	398000	60400	41400
Cooler duty(KW)	0.0	1727	271	179
Cost of cooling water (\$/y)	0.0	18300	2870	1900
Heater duty(KW)	0.0	261	73	43
Cost of low pressure steam (\$/y)	0.0	103840	29040	17110
Total Operating cost (\$/y)	1313600	933740	1156510	1117510
Operating cost savings (%)	0.0	28.92	11.96	14.93
Capital cost(\$)				
Column	660817	660817	645107	638132
Trays	53691	53691	51845	51032
Condenser	206930	0.0	173824	174362
Reboiler/Intermediate reboiler	116697	254705	124068	133180
Trim-reboiler	0.0	55993	101911	101410
Compressor	0.0	2341247	499254	366171
Cooler	0.0	151864	26458	20100
Heater	0.0	18183	10579	7254
Total capital cost (\$)	1395389	3893754	1981522	1836223
TAC(\$/y)	1521555	1514026	1451816	1391162
TAC savings (%)	0.0	0.50	4.58	8.57

Table 4. Comparison of Estimated Capital and Operating Costs in Case 2

Items	DWC	VRC-DWC	SRVRC-DWC	IC-SRVRC-DWC
Condenser duty (KW)	6088	0.0	2633	2819
Cost of cooling water (\$/y)	65000	0.0	27900	29900
Reboiler duty (KW) (steam-heated)	6175	1166	2910	3067
Reboiler duty (KW) (compressed vapor-heated)	0.0	5009	4190	4169
Cost of medium pressure steam (\$/y)	2625000	508400	1237100	1303800
Compressor duty (KW)	0.0	1196	328	316
Cost of electricity (\$/y)	0.0	669000	183000	177000
Cooler duty (KW)	0.0	2637	639	596
Cost of cooling water (\$/y)	0.0	28000	6800	6300
Heater duty (KW)	0.0	370	120	118
Cost of low pressure steam (\$/y)	0.0	147200	47740	46950
Total Operating cost (\$/y)	2690000	1352600	1502540	1563950
Operating cost savings (%)	0.0	49.72	44.14	41.86
Capital cost (\$)				
Column	1671253	1671253	1742207	1762292
Trays	195736	195736	207934	211429
Condenser	451313	0.0	261748	273603
Reboiler/Intermediate reboiler	142509	418341	408963	391172
Trim-reboiler	0.0	48334	87320	90374
Compressor	0.0	3586359	1241454	1204086
Heater	0.0	30483	14611	14132
Cooler	0.0	251452	100068	94479
Total capital cost (\$)	3394306	7135453	5039376	5028428
TAC (\$/y)	3195853	2415996	2253558	2313337
TAC savings (%)	0.0	24.40	29.49	27.61

Table 5. Comparison of Estimated Capital and Operating Costs in Case 3

Items	DWC	VRC-DWC	SCVRC-DWC	IR-SCVRC-DWC
Condenser duty (KW)	7662	0.0	2326	2363
Cost of cooling water (\$/y)	81000	0.0	24700	25100
Reboiler duty (KW) (steam-heated)	7749	1834	2890	2905
Reboiler duty (KW) (compressed vapor-heated)	0.0	5915	4979	5002
Cost of medium pressure steam (\$/y)	3294000	779700	1228600	1235000
Compressor duty (KW)	0.0	1408	380	374
Cost of electricity (\$/y)	0.0	787000	57690	209000
Cooler duty (KW)	0.0	3373	1003	974
Cost of cooling water (\$/y)	0.0	36000	10600	10300
Heater duty (KW)	0.0	210	145	145
Cost of low pressure steam (\$/y)	0.0	83550	57690	57690
Total Operating cost (\$/y)	3375000	1686250	1534590	1537090
Operating cost savings (%)	0.0	50.04	54.53	54.46
Capital cost (\$)				
Column	1989303	1989303	1907562	1913648
Trays	244086	244086	229640	230706
Condenser	546444	0.0	253477	256104
Reboiler/Intermediate reboiler	163225	524538	463139	467445
Trim-reboiler	0.0	63985	85862	86228
Compressor	0.0	4099854	1400673	1382512
Heater	0.0	20629	20232	20232
Cooler	0.0	309763	67319	66058
Total capital cost (\$)	4059753	8368853	5496505	5495110
TAC (\$/y)	3980025	2933460	2353734	2356026
TAC savings (%)	0.0	26.30	40.86	40.80

Graphical Abstract

(a)

(b)

(c)

(d)

Schematic diagrams of the (a) SCVRC-DWC, (b) IR-SCVRC-DWC, (c) SRVRC-DWC and (d) IC-SRVRC-DWC