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Application of a thermally coupled distillation column with separated main columns to gas concentration process

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Abstract−A modified fully thermally coupled distillation column (FTCDC) for operability improvement is utilized in a gas concentration process. The column consists of a prefractionator and two separated main columns having high distillation efficiency and flexible control structure. The operability of the proposed column is evaluated by examining the open-loop dynamic responses of step input variations with the HYSYS simulation. The simulation result indicates that the modified system can give better control than the original FTCDC. The energy saving and reduction of construction cost are discussed, and the ease of vapor flow manipulation and the elimination of a compressor in the vapor transfer are also evaluated as possible improvements.

Key words: Thermally Coupled Distillation, Gas Concentration Process, Energy-Efficient Distillation, Multi-Component Distillation

INTRODUCTION

Though a fully thermally coupled distillation column (FTCDC), which consists of a prefractionator and a main column interlinked with two-way transfers, consumes less energy than a conventional distillation system for a given separation, its practical utilization has not been active due to the operational difficulty of the column. There have been many studies to alleviate the problem [1-7]. Agrawal and Fidkowski [1] proposed more operable arrangements of distillation sections in the FTCDC for easy vapor transfer, and later they introduced modified structures of the FTCDC by eliminating one of two-way transfers between the prefractionator and main column for easy operation of the system [2]. Wolff and Skogestad [4] examined various control structures of the FTCDC to find an optimum control scheme. A configuration of partially separated main columns has been proposed to improve the operability by Kim [5]. Also, a fully separated main column was also introduced, and the improvement of control performance was investigated by examining dynamic response of product compositions when operational variables were altered [6].

A gas concentration process produces ethane, propane and butane from various sources of raw gas by-products, which include crude refining, naphtha reformation and heavy oil cracking processes. The process practically utilizes conventional binary distillation columns in direct sequence. When an FTCDC replaces the conventional system, some 18% less heat duty is required in the same separation [8]. However, the FTCDC has not been implemented in the process. Because the handling of gas processing unit is difficult, field engineers are reluctant to adopt the FTCDC in the unit due to the known difficulty of the FTCDC operation.

In this study, an FTCDC with separated main columns is applied to the gas concentration process, and the performance of energy conservation compared with the original FTCDC is examined. The dynamic response of the proposed distillation system is investigated to find a proper control structure for easy operation. In addition, various improvements are discussed in the operation and construction of the separated FTCDC.

DESIGN PROCEDURE

In the practical design of distillation columns, an optimum rate of reflux flow is determined first, and the structural information, such as total number of trays and feed location, is designed later. An FTCDC has interlinking streams of two-way transfer between the prefractionator and main column, and therefore the liquid flow rate of the streams cannot be determined first due to the unknown compositions of the streams. Instead, a structural design is conducted first, and then the operating variables, such as liquid and vapor flow rates, are calculated by using process simulation. For the purpose, a three-column model [9] has been utilized in the structural design. The model assumes that the FTCDC is composed of three binary distillation columns: one for the prefractionator and two for upper and lower sections of the main column. In the model one-way connections between the prefractionator and main column are used, though those in the FTCDC are interlinked with two-way transfer. This simplification results in some error in the design.

The structure of an original FTCDC has been designed by using the column profile of equilibrium distillation [10]. Because the column profile of the FTCDC is similar to the equilibrium distillation having an ideal distillation efficiency, the column consumes less energy than a conventional system. The proposed FTCDC system of separated main columns as shown in Fig. 1 is based on the original FTCDC having a connected main column, and therefore the design procedure of the original column can be used here and is briefly explained.

When feed tray composition is assumed to be the same to feed composition, the column profile of the prefractionator is close to a

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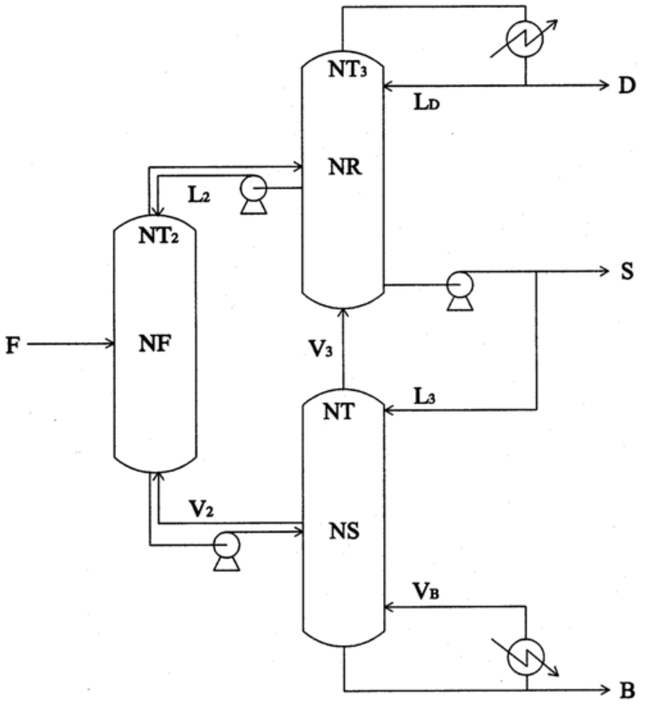


Fig. 1. A schematic diagram of a fully thermally coupled distillation column with separated main columns.

residue curve of ternary mixture for the ideal distillation efficiency [11]. Therefore, the liquid composition one stage above the feed stage is the vapor composition computed from a vapor-liquid equilibrium (VLE) in the stage. In this study the Peng-Robinson EOS was employed in the VLE computation. A repeated application of the stage-to-stage computation gives the column profile of upper section of the prefractionator. The profile of the lower section is also obtained by using the VLE and the stage-to-stage computation beginning with the feed composition. Note that a liquid composition is computed from the equation and used as the vapor composition one stage below the feed stage. The same procedure is applied to the computation of liquid profile in the main column beginning at the side draw tray and the side draw composition. The end tray compositions of the prefractionator are determined by comparing column profiles of the computed prefractionator and main column and matching the compositions of interlinking trays in close.

Now the total number of trays in the prefractionator and main column, location of feed and side draw and the interlinking trays in the main column are found from the result of the stage-to-stage computation. Because the structural design of this study is based on the ideal distillation efficiency, where the tray number is a minimum, the result has to be adjusted for a practical column. For a common design guideline of reflux flow computation, i.e., 1.3 times the minimum reflux flow, twice the minimum tray number is used in the distillation system design [12]. The tray numbers are multiplied by two for a practical FTCDC, and the numbers are listed in Table 1 as an original FTCDC. The proposed system of this study has separated main columns at the tray of side draw in the original FTCDC as shown in Fig. 1, and therefore the tray numbers are easily determined by simply taking the upper section of the main column from side draw tray as the upper main column of the proposed FTCDC. And the lower section becomes the lower main column. Table 1 contains the tray numbers of the proposed FTCDC too.

After the structural design of the proposed system is completed, the operational variables of the proposed FTCDC can be found from process simulation. A commercial software, the HYSYS, was utilized in the simulation. The information of tray numbers and column pressure is needed to begin the computation. For the given feed and product composition summarized in Table 2, an iterative computation is conducted with different numbers of operational variables until the product amount and composition are yielded. The simulation results are listed in Table 1.

RESULTS AND DISCUSSION

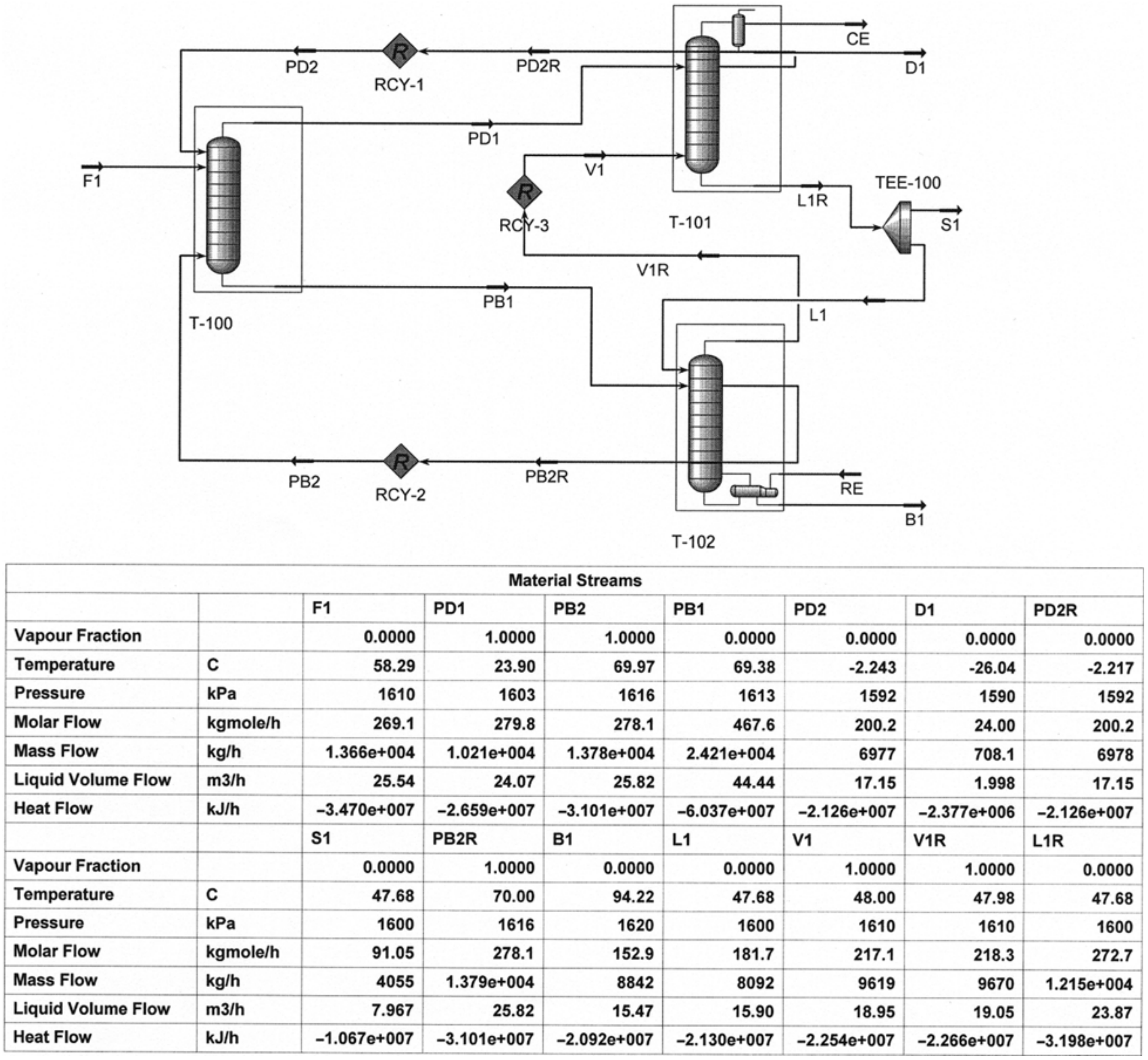
The feed and product compositions are grouped in three, considering relative volatility and their amount as given in Table 2. Using the three groups the design procedure described above can be ap-

Table 1. Tray numbers from structural design and operating conditions of original and proposed FTCDCs in a gas concentration process. Tray numbers are counted from the top

Name	Proposed FTCDC			Original FTCDC	
	Prefractionator	Upper	Lower	Prefractionator	Main
(Structural)					
Number of trays	10	23	32	10	55
Feed/side product	5	5	21	5	23
Interlinking stages					5, 43
(Operating)					
Pressure [kPa]	1603	1590	1610	1603	1573
Feed [kmol/h]	269.1	276.9	468.4	269.1	
Overhead [kmol/h]		24.0			24.0
Bottom [kmol/h]		91.78	152.9		152.9
Side [kmol/h]		200.2	276.0		92.07
Reflux [kmol/h]	200.2	566	190.6	200.0	590
Vapor boilup [kmol/h]	276.0	229.7	500.7	275.9	511.9
Heat duty [GJ/h]			7.210		7.361

Table 2. Flow rates of feed and products of original and proposed FTCDCs in a gas concentration process with unit of kmol/h

Component	Feed	Proposed FTCDC			Original FTCDC		
		Overhead	Side	Bottom	Overhead	Side	Bottom
(Light)							
Methane	0.9879	0.9879	0.0000	0.0000	0.9877	0.0000	0.0000
Ethane	22.966	22.989	0.0698	0.0000	22.917	0.0859	0.0000
Propene	0.5729	0.0005	0.5280	0.0085	0.0049	0.5474	0.0096
(Intermediate)							
Propane	92.553	0.0232	88.487	3.6817	0.0849	89.115	3.4366
(Heavy)							
i-Butane	75.966	0.0000	2.0598	73.669	0.0000	1.7765	73.890
i-Butene	3.2506	0.0000	0.0577	3.1931	0.0000	0.0472	3.1985
n-Butane	71.739	0.0000	0.5774	71.159	0.0000	0.4961	71.206
i-Pentane	1.1720	0.0000	0.0003	1.1719	0.0000	0.0003	1.1720
n-pentane	0.0171	0.0000	0.0000	0.0171	0.0000	0.0000	0.0171
Total	269.13	24.000	91.779	152.90	23.995	92.069	152.93



Material Streams

		F1	PD1	PB2	PB1	PD2	D1	PD2R
Vapour Fraction		0.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000
Temperature	C	58.29	23.90	69.97	69.38	-2.243	-26.04	-2.217
Pressure	kPa	1610	1603	1616	1613	1592	1590	1592
Molar Flow	kgmole/h	269.1	279.8	278.1	467.6	200.2	24.00	200.2
Mass Flow	kg/h	1.366e+004	1.021e+004	1.378e+004	2.421e+004	6977	708.1	6978
Liquid Volume Flow	m3/h	25.54	24.07	25.82	44.44	17.15	1.998	17.15
Heat Flow	kJ/h	−3.470e+007	−2.659e+007	−3.101e+007	−6.037e+007	−2.126e+007	−2.377e+006	−2.126e+007
		S1	PB2R	B1	L1	V1	V1R	L1R
Vapour Fraction		0.0000	1.0000	0.0000	0.0000	1.0000	1.0000	0.0000
Temperature	C	47.68	70.00	94.22	47.68	48.00	47.98	47.68
Pressure	kPa	1600	1616	1620	1600	1610	1610	1600
Molar Flow	kgmole/h	91.05	278.1	152.9	181.7	217.1	218.3	272.7
Mass Flow	kg/h	4055	1.379e+004	8842	8092	9619	9670	1.215e+004
Liquid Volume Flow	m3/h	7.967	25.82	15.47	15.90	18.95	19.05	23.87
Heat Flow	kJ/h	−1.067e+007	−3.101e+007	−2.092e+007	−2.130e+007	−2.254e+007	−2.266e+007	−3.198e+007

Fig. 2. A process flow diagram and operating conditions of a gas concentration process.

plied to the gas concentration process, though the feed is a mixture of nine components. In the examination of dynamic behavior of the proposed FTCDC, the compositions of ethane, propane and i-butane have been tracked as key components in the light, intermediate and heavy products, respectively.

The structural design gives 55 trays for the main column in the original FTCDC, and the number of side draw trays is 23. Therefore, the main column is separated at the 23rd tray from the top for the proposed FTCDC, and the number of trays in the upper and lower main columns is 23 and 32, respectively. While the interlinking location in the upper main column is unchanged, that in the lower column is recounted from the location in the original FTCDC. Because the prefractionator is common in both distillation systems, its number of trays and feed location are the same.

For easy vapor flow, the column pressure in the upper main column is set to the lowest, and that in the lower column is to the highest. The pressure of the prefractionator is middle and is equal to that in the original FTCDC. The manipulation of vapor flow in the original FTCDC is difficult due to two-way connection between the prefractionator and main column. By setting the pressures of two columns different, one of the vapor flows can be made without a compressor, but the other has to utilize a compressor to flow against the higher pressure column. This is one of the reasons why a divided-wall column is favorable in practical applications. On the other hand, the structure of the separated main columns has three different pressure settings for the three columns so as to flow the vapor easily in the intended direction. In that way no compressor is necessary for the vapor flow. Instead, pumps are required for the liquid flow in the opposite direction to the vapor flow, which are much cheaper and easier to handle compared with a compressor.

The operating conditions for the three products listed in Table 2 were found from the HYSYS simulation. The required heat duty

Table 3. Input changes in the proposed and original fully thermally coupled distillation columns for operability comparison. Units are in kmol/h

Variable	Proposed FTCDC			Original FTCDC		
	Reflux	Lower liq.	Vapor boilup	Reflux	Side draw	Vapor boilup
Initial value	554.7	172.5	492.5	746.8	92.0	514.7
Applied value	547.5	165.6	500.4	736.6	95.8	522.5
Change [%]	−1.3	−4.0	+1.6	−1.3	+4.0	+1.6

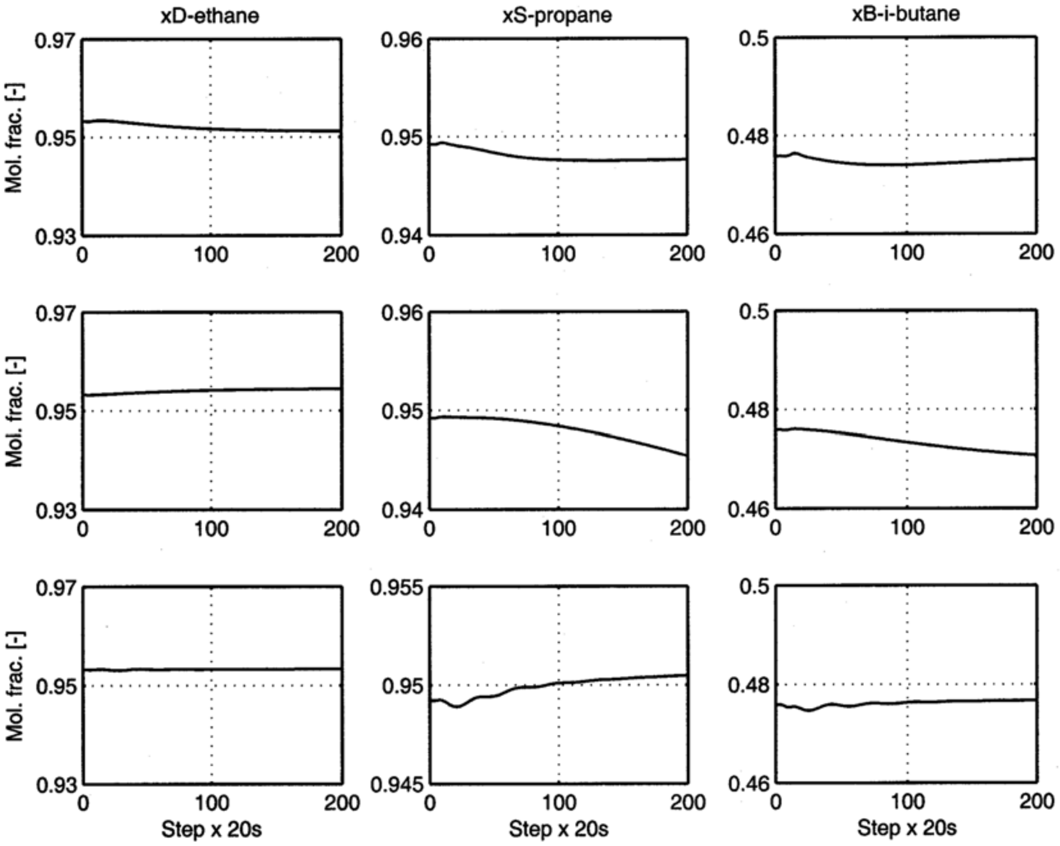


Fig. 3. The responses of overhead, side draw and bottom product specifications with step changes of reflux, side draw and vapor boilup rates in an original FTCDC for a gas concentration process. Top three figures are of reflux flow rate, middle three are of side draw rate and the bottom three are of vapor boilup rate.

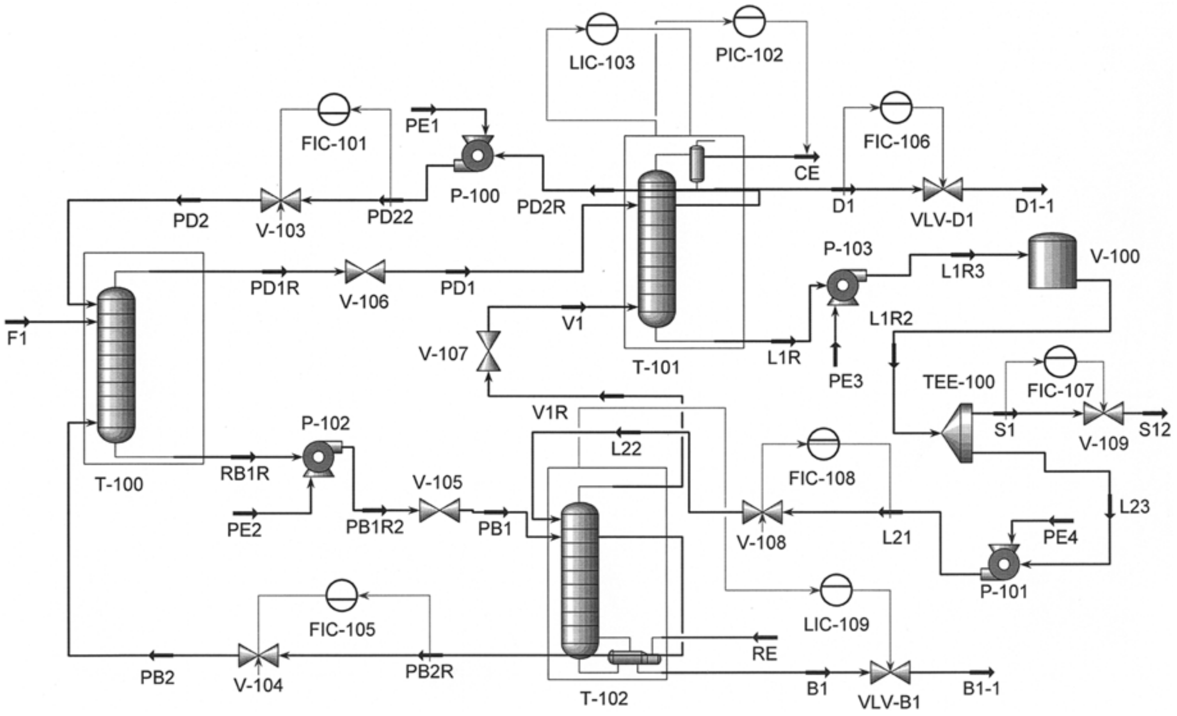


Fig. 4. A process and instrumentation diagram of a gas concentration process for dynamic simulation.

of the proposed FTCDC is 2% less than that of the original, but the comparison is not significant because the amount and composition of side product from the proposed are a little less due to the error of numerical computation. Otherwise, the difference of the operating conditions in both systems is not noticeable. A process flow diagram of the proposed FTCDC for the steady-state HYSYS simulation is demonstrated in Fig. 2. The details of stream conditions and compositions are also included in the figure as a table.

A key improvement of the modification of this study is the enhancement of operability. Poor operability has been a major factor of field engineers' reluctance in the implementation of the FTCDC. The operability was examined by comparing the dynamic responses of step changes of three inputs in the original and proposed FTCDCs. Table 3 lists the number of applied variations. A 3×3 control structure proposed by Wolff and Skogestad [4] was implemented in the original FTCDC, and three inputs of reflux flow, side draw and vapor boilup rates were used for the specification control of overhead, side and bottom products. Fig. 3 shows the open-loop dynamic responses of the step changes of reflux flow, side draw and vapor boilup rates. The compositions of ethane, propane and i-butane are the key components of overhead, side and bottom products, respectively. When the reflux flow rate is varied, the top three plots demonstrate the responses of the compositions. A noticeable variation is observed in the composition of side product, while the compositions of side and bottom products are altered with the change of side draw rate. In the change of vapor boilup rate, the side product composition has a small increase. For the 3×3 control structure, at least one response has to be given to each of three controlled variables. However, the composition of overhead product is barely changed, whereas that of side product varies by all three manipulated variables resulting in a coupling problem among controlled variables.

In the separated main column system, the process can be arranged as illustrated in Fig. 4 for the operability improvement. The figure is a process and instrumentation diagram for dynamic simulation. Although the separate control of liquid flow in the lower main column is not available in the original FTCDC due to the integration of upper and lower columns, the system of this study can install a storage tank between the upper and lower columns and separately adjust the liquid flow in the lower column. The step responses of reflux, lower column liquid and vapor boilup rates are shown in Fig. 5. The scales of the plots are the same as in Fig. 3 for fair comparison. The change of reflux flow rate gives the composition variation in overhead and side product, and the liquid flow in lower column varies the bottom product composition. Also, the variation of vapor boilup rate leaves the composition change of side product. Comparing with the response of the original FTCDC indicates that a 3×3 control in the proposed system can be much better due to the availability of manipulated variables for each controlled variables and less coupling among the variables.

A gas concentration process handles relatively large amount of gas products due to the large production of other products from crude oil, and therefore the reduced amount of energy demand in the process is very large when an energy-efficient distillation system is utilized. For example, the total domestic propane production is 29,000 barrels per day, while the production of this study is 1,230 barrels per day and an energy saving of 17.6% is expected by utilizing the FTCDC [13]. In other words, some 890 GJ of heat can be saved daily. The conservation reduces not only the energy cost but the construction cost of heat exchangers. Moreover, the structure of separated main columns makes the construction of the distillation system simpler than the original FTCDC, because the column construction is more flexible due to its structural similarity to the ex-

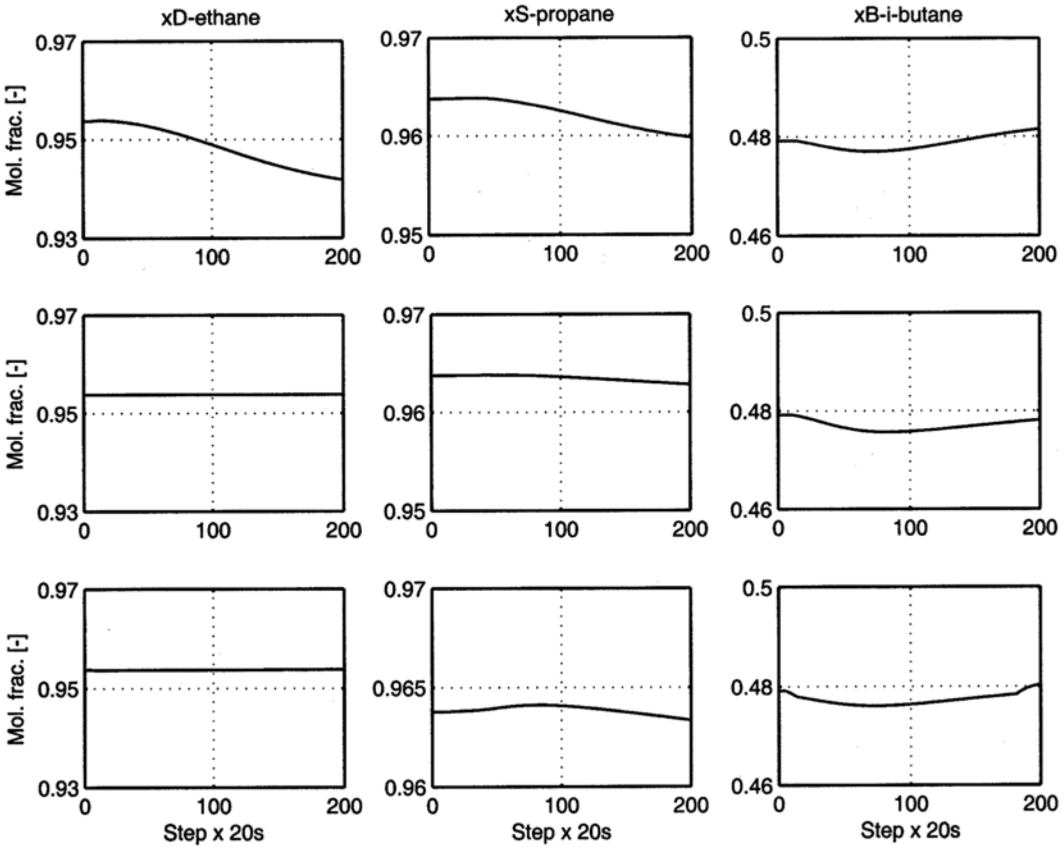


Fig. 5. The responses of overhead, side draw and bottom product specifications with step changes of reflux, lower column liquid and vapor boilup rates in the proposed FTCDC for a gas concentration process. Top three figures are of reflux flow rate, middle three are of lower column liquid rate and the bottom three are of vapor boilup rate.

isting distillation systems.

CONCLUSIONS

A fully thermally coupled distillation column (FTCDC) having separate main columns is utilized in a gas concentration process for the saving of energy consumption and improved operability. In the structural design of the column, a column profile of ideal equilibrium distillation is employed, and a steady-state simulation is conducted by using the HYSYS to find the operating conditions. For the examination of the operability, a dynamic simulation is carried out with open-loop step changes of inputs. The results of performance evaluation indicate that the proposed system handles vapor flow better than the original FTCDC, and the operability is improved to give better control of the specifications of three products using reflux, lower column liquid and vapor boilup rates. In addition, the elimination of a compressor for vapor flow makes the construction and operation of the FTCDC easier than the original.

ACKNOWLEDGMENTS

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NOMENCLATURE

B : bottom product
D : overhead product
F : feed
L_2 : prefractionator liquid flow rate [kmol/h]
L_3 : lower main column liquid flow rate [kmol/h]
L_D : upper main column liquid flow rate [kmol/h]
NF : feed tray
NR : interlinking tray in upper main column
NS : interlinking tray in lower main column
NT : total tray number in lower main column
NT_2 : total tray number in prefractionator
NT_3 : total tray number in upper main column
S : side product
V_2 : prefractionator vapor flow rate [kmol/h]
V_3 : upper main column vapor flow rate [kmol/h]
V_B : vapor boilup rate [kmol/h]

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