Energy－Saving Process Intensification of an Oil Refinery Distillation Plant
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Energy-Saving Process Intensification of an Oil Refinery Distillation Plant by an Internal Heat Integration Method

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Abstract

A new approach for energy-saving process intensification was demonstrated by a heat integration method taking for instance the C-5 splitter distillation plant existing for extracting pure c-pentane from a petroleum hydrocarbon mixture obtained by naphtha cracking. A process simulation analysis was made without loosening the specifications of separation of the existing plant. A new process-intensified distillation plant was designed consisting of two heat integrated distillation columns (named HIDiC column 1&2) and a compressor installed between the first HIDiC rectifying and stripping section. It has been found that advantageous process intensification with a great effect of energy-saving can be realized without installing another compressor for the second HIDiC column.

Keywords: Multi-component Distillation, Heat Integration, Energy Saving, Process Intensification

1. Introduction

Recent heat integrated distillation technology developed as one of the Japanese governmental projects for prevention against global warming is of great importance because the thermal energy consumed in distillation processes occupies a large part in the total energy consumption of chemical industry. One possible way except for the so-called vapor recompression method pumping up the thermal energy released from the overhead condenser to the bottom reboiler is to raise the pressure of the rectifying section by a compressor so as to make the boiling point of the rectifying section higher than that of the thermally-contacted stripping section. The internal reflux liquid of the stripping section is partially vaporized by receiving the latent heat discharged due to partial vapor condensation in the pressurized rectifying section. This is a basic

configuration of the internal heat integrated distillation column (HIDiC) systems devised in order to reduce heat duties of the reboiler and condenser of a single column. Figure 1 shows how to constitute a HIDiC system in place of a single conventional column. The energy saving method of this kind first proposed by Mah et al. (1977) is called the secondary reflux and vaporization (SRV) method. Takamatsu et al. (1988) proposed a design method for a packed-column-type HIDiC system.

This type of HIDiC systems were reviewed in general by Nakaiwa et al. (2003). A packed-column HIDiC pilot plant has first been constructed in place of the first column of the existing plant. (reported by Horiuchi et al. 2005). This pilot plant achieved an energy-saving rate higher than 50% of the energy consumption of the first column reboiler. It has been demonstrated by Kataoka et al.(2006) that the internal heat integration applied between two different columns without installing a compressor does not bring on a great energy-saving rate as compared to the standard HIDiC system equipped with a compressor. The purpose of the present work is to give an impact of process intensification accompanied with a great effect of energy saving on the distillation technology of chemical industry.
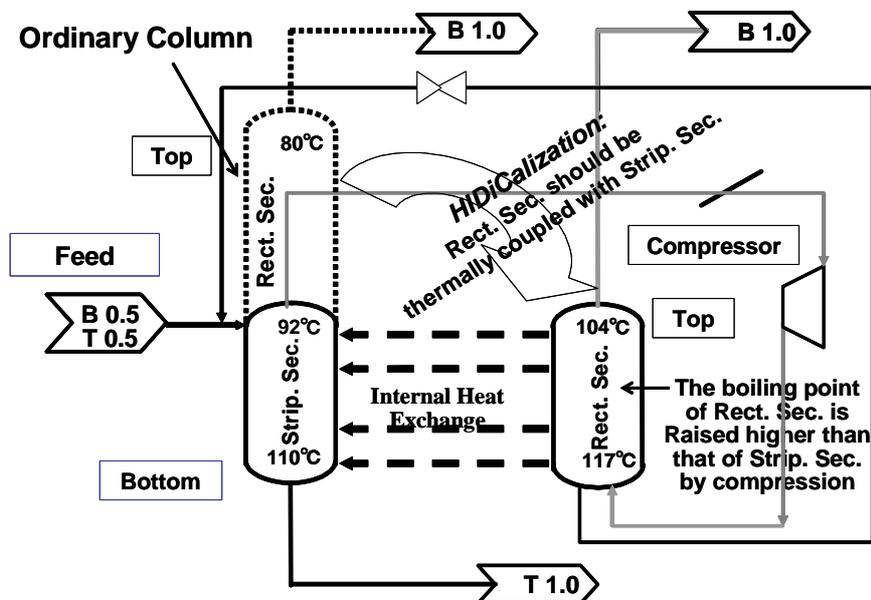
Fig.1 Principle of internal heat integration by pumping the latent heat discharged from the rectifying section up to the stripping section. The numerals given as an example are the roughly-estimated compositions in mole fraction and boiling points of a binary mixture of benzene and toluene.

2. Research Subject and Objectives

This paper deals with a novel HIDiC system to be applied for the C5-splitter distillation plant extracting c-pentane from petroleum hydrocarbon mixtures obtained by naphtha cracking. As shown in Fig.2, the existing plant selected as a subject of national project consists of three columns connected in series. Table 1 indicates an actual operational record of the composition and total flowrate measured or calculated

F= 1650 kg/h
x_F= 0.369

F 1 T1 2 D1 3

4 T2 5 D2 6 8 T3 9 D3

Pure c-pentane

x_D3= 0.983

55 stages   40 stages   40 stages

7 W1 W2 10 W3

Operation Pressure: P= 1 atm
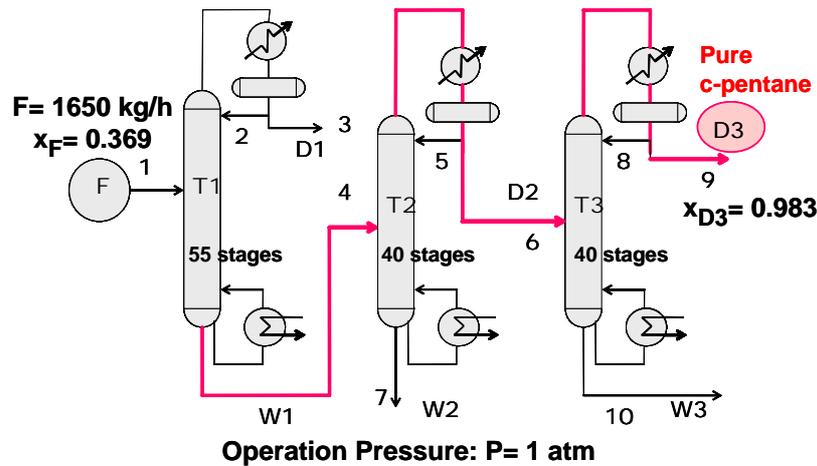
Fig.2 The existing C5-splitter for extracting pure c-pentane as the third overhead product D3 from a twelve-component mixture of petroleum hydrocarbons.

Table 1 Mass balance data obtained at each stream by practical operation of the existing C5-splitter.

Stream number	1	2	3	4	5	6	7	8	9	10
Component (wt%)										
n-Butane	0.04	0.20	0.35							
i-Pentane	1.80	9.61	10.34							
n-Pentane	14.89	85.98	84.14	0.08	0.27	0.28		0.37	0.35	
2,2-Dimethylbutane	0.22	0.06	0	0.23	0.53	0.57		0.64	0.69	
Cycopentane	36.90	4.15	5.17	45.09	82.06	81.90	1.50	98.27	98.26	7.87
2,3-Dimethylbutane	1.49			1.92	1.67	1.70	2.17	0.29	0.35	7.87
2-Methylpentane	13.57			15.87	8.93	8.91	24.00	0.43	0.35	47.24
3-Methylpentane	4.71			5.98	2.10	2.12	10.50			11.82
n-Hexane	11.43			13.19	2.30	2.26	26.00			12.60
Methyl-cyclopentane	13.24			15.49	1.97	1.98	31.33			11.02
Benzene	0.43			0.54	0.07	0.14	1.17			0.79
Cyclohexane	1.28			1.61	0.10	0.14	3.33			0.79
Total flow rate (kg/h)	1650	3500	310	1340	3000	705	635	3750	579	126

at the pipeline sections numbered in Fig.2. In this plant, c-pentane is the most-valuable intermediate key component. The first column withdraws most of the lighter components more-volatile than c-pentane as the first overhead product D1 (Stream #3). The purpose of the second columns is to obtain c-pentane-rich solution (about 82 wt%) as the second overhead product D2 (Stream #6) by cutting most of the heavier components less-volatile than c-pentane. The less-volatile components remaining in Stream #6 are finally separated as the bottom product of the third column. Pure c-pentane (97 wt% or more) is extracted as the third overhead product D3 (stream #9) from the third column. Those three columns have the number of actual trays of 55, 40 and 40, respectively.

Figure 3 shows a well-known fundamental heat integration method applying the internal heat exchange between the rectifying and stripping section of a single column. As shown in the figure, the internal heat exchange is expressed with imaginary heat exchangers.
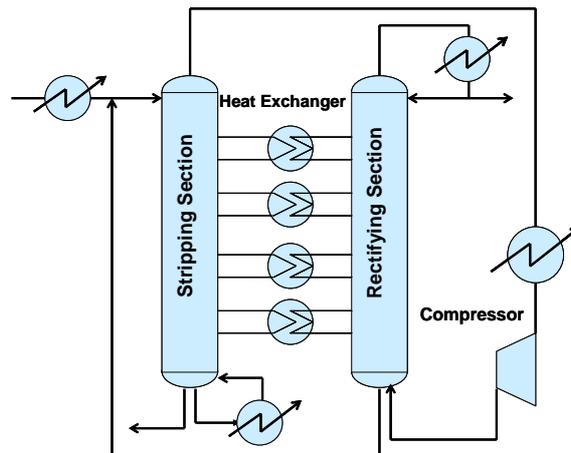
Fig.3 Schematic picture of a single HIDiC distillation column constituted
by an internal heat integration method.

In this case, a compressor is necessary to raise the boiling point of the rectifying section higher than that of the stripping section. The energy consumed by the reboiler can be reduced by the effect of heat pumping from the rectifying to the stripping section.

For the case of HIDiC system devised for energy saving of the first single column, the compression ratio of the compressor, i.e. the pressure ratio of the rectifying to the stripping section, is the primary parameter of HIDiC condition controlling the internal heat integration. The main issue of this study is how an effective HIDiC C5-splitter should be constituted in place of the existing plant by making an energy-saving analysis. It is a primarily important issue how much the heat duty required for the reboilers of the three columns can be reduced by this method. The rate of energy-saving, therefore, was set higher than 30 % of the energy consumption of the existing plant as the target of the HIDiC project.

3. A New HIDiC System Constituted for Process Intensification

3.1 Constitution of a total HIDiC system in place of the existing C5-splitter plant

There are various ways of combination of those columns available for heat integrated distillation systems. The purpose of this research is how to constitute a total system with two HIDiC columns in place of three columns of the existing C5-splitter from a view point of process intensification.

The following evolutional ideas have been adopted as the assumption for process simulation:

(1) As different from the actual operation of the existing C5-splitter, the first HIDiC column is made to discharge c-pentane-rich vapor from the top of the rectifying section cutting the mixture between c-pentane and 2,3-Dimethylbutane.

(2) Only one compressor is installed between the rectifying and stripping sections of the first HIDiC column.

(3) The top vapor issuing from the first HIDiC rectifying section is supplied as it is, into the bottom of the following second HIDiC rectifying section. This

method can therefore omit a compressor for the second HIDiC column.

(4)   An overhead condenser is installed at the top of the second HIDiC stripping section. The condensate obtained by this condenser is refluxed not only into the second HIDiC stripping section but also into the first HIDiC rectifying section. This idea is distinct from the basic concept of the existing HIDiC method.

These ideas can constitute a total HIDiC system in place of the existing C5-splitter as shown in Figure 4.

Since the pressurized vapor from the top of the first HIDiC rectifying section can be supplied as it is, directly into the bottom of the second HIDiC rectifying section, the second HIDiC column does not require a compressor. This system should have two overhead condensers and two bottom reboilers. It is one of peculiarities to set up one of the two condensers at the top of the second HIDiC stripping section. Pure c-pentane can be obtained as the bottom product of the second HIDiC stripping section. The first HIDiC rectifying section can receive the reflux liquid from this condenser of the second HIDiC stripping section.

Figure 5 shows the flow diagram of the HIDiC system superseding the existing C5 splitter. The double-tube column has the rectifying section inside the inner tube and the stripping section in the annular space formed between the outer and inner tubes. The rectifying section of the first HIDiC column pressurized by the compressor is in thermal contact with the first HIDiC stripping section operated at normal pressure.
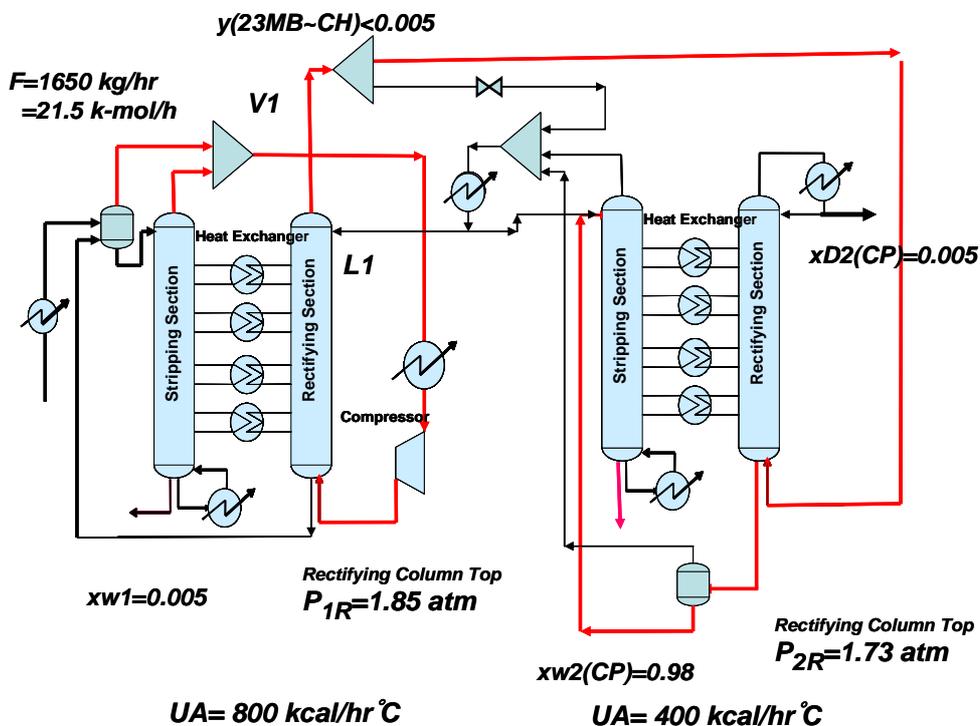
Fig.4 Schematic picture of a total HIDiC system devised in place of C5-splitter.

Pr: Preheater, Cd: Condenser, Fl: Flash Drum, Cm: Compressor,
Rb: Reboiler, Sp: Splitter, Mx: Mixer
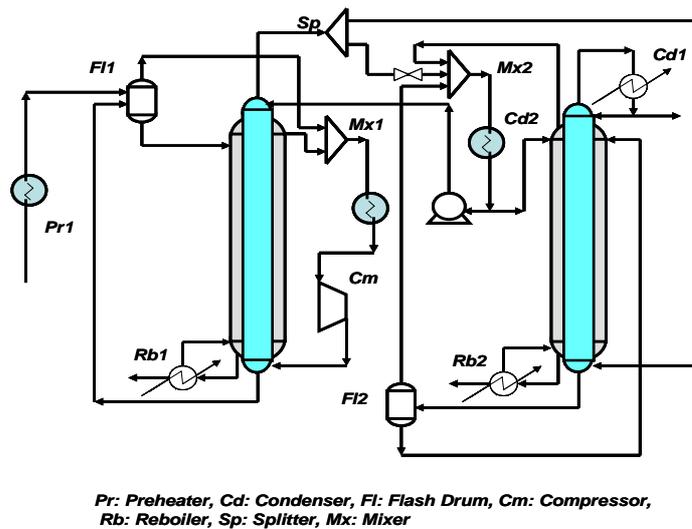
Fig. 5 Flow diagram of a HIDiC plant designed by a new HIDiC system constitution method

The wall of the inner tube serves as the heat transfer interface. The first HIDiC rectifying and stripping sections are assumed to have 35 theoretical stages, respectively. The original first column has 55 actual trays, i.e. 39 theoretical stages.

It is a great economical merit that if the top vapor from the first HIDiC rectifying section is supplied directly into the second HIDiC rectifying section, it can eliminate the necessity for installing another compressor to pressurize the second HIDiC rectifying section. The overhead condenser for the reflux into the top of the second HIDiC stripping section is also characteristic of the new HIDiC system constitution method. Some portion of the reflux liquid is fed back into the first HIDiC rectifying section. Owing to the internal heat exchange in both the HIDiC columns, the additional vapor condensation occurring in each rectifying section causes the additional vaporization of the internal reflux liquid flowing down in the corresponding stripping section. Therefore this internal heat exchange brings a great reduction of heat duty required for the bottom reboilers. The reduced vapor flow rate at the top of each rectifying section also indicates a great reduction of heat duty for the corresponding overhead condenser.

The number of theoretical stages of HIDiC Column #1 and Column #2 is assumed as 35 + 35 stages for Column #1 and 42 + 42 stages for Column #2. For example, 35 theoretical stages of the rectifying section of HIDiC Column #1 with no overhead condenser is thermally-contacted with the 35 theoretical stages of the stripping section of HIDiC Column #1 having a bottom reboiler.

3.2 Specifications of separation and internal heat exchange for simulation analysis

Referring to the actual operation data of mass balance shown in Table 1, the heat duties of the overhead condenser, bottom reboiler and the preheater of the existing three columns were calculated by simulation. The calculated result shown in Table 2 is adopted as the comparison basis.

Table 2 Heat duties required for the three columns of the existing C5-splitter

	Column #1	Column #2	Column #3	Total Heat Duty
OH Condenser	-0.3588 Gcal/hr	-0.3315 Gcal/hr	-0.3971 Gcal/hr	-1.0874 Gcal/hr
BTM Reboiler	0.3892 Gcal/hr	0.3311 Gcal/hr	0.3976 Gcal/hr	1.1179 Gcal/hr
Preheater	0.0039 Gcal/hr			

1 Gcal/hr = 10^9 cal/hr = 4.184 GJ/h

Table 3 shows specifications of separation with the fixed and variable key parameters for the HIDiC system.

The bottom pressure of the first HIDiC rectifying section is controlled directly by the compressor but the bottom pressure of the second HIDiC rectifying section is automatically settled down to a certain value depending on the pressure drop in the first HIDiC rectifying section and the pipeline leading to the second HIDiC rectifying section.

The specifications of operation were determined for the new HIDiC system to obtain pure c-pentane (98 wt%) from the bottom of the second HIDiC stripping section so as to attain the same separation efficiency as the existing C5-splitter.

The main purpose of the first HIDiC column is to sharply cut the mixture between c-pentane and 2,3-dimethylbutane.

As indicated in Table 3, the vapor issuing from the top of the first HIDiC rectifying section should have a key separation condition keeping the total concentration $y_{D1<cp}$ of the components less-volatile than c-pentane as low as possible.

This condition is given by keeping the total concentration of the components less-volatile than c-pentane lower than or equal to 0.005 in mass fraction in the overhead vapor issuing from the top of the first HIDiC rectifying section.

The second HIDiC reflux ratio **R(2)** is variable for keeping the separation specs of the second HIDiC overhead and bottom products:

The separation specs are fixed in mass fraction of c-pentane as

$x_{W2} = 0.98$ and $x_{D2} = 0.005$

Table 3 Column constitution, separation specs and key parameters for HIDiC Column #1 & 2

	1st HIDiC column		2nd HIDiC column	
	Stripping section	Rectifying section	Stripping section	Rectifying section
Pressure at column top (atm)	$P_{1S} = 1.0$	$P_{1R} = 1.85$	$P_{2S} = 1.0$	$P_{2R} = 1.73$
Pressure drop/stage (atm/stage)	0.003	0.003	0.003	0.003
Number of theoretical stages	35(R)	35	42(R)	42(C)
Feed stage	#1	#35	#1	#42
Overhead or bottom product (c-pentane mass fraction)	$x_{W1} = 0.005$	y_{D1} $_{<cp} = 0.005*$	$x_{W2} = 0.98$	$x_{D2} = 0.005$
Reflux ratio		R(1) variable	variable	R(2) variable
Overall heat transfer capacity	UA=800 kcal/hr ˚ C		UA=400 kcal/hr ˚ C	

* This condition implies that the overhead vapor issuing from the rectifying section of the first HIDiC column should have 0.005 as the total mass fraction of the components less-volatile than c-pentane.

Table 3 indicates that the simulation purpose should be to analyze how much energy consumption of the two reboilers the new HIDiC system can reduce under the given separation specs by changing the external reflux ratio *R(1)* and *R(2)*. The feed stage of the first HIDiC column is the top of the stripping section and the vapor issuing from the top of the stripping section is compressed by the compressor into the bottom of the pressurized rectifying section. The liquid from the bottom of the rectifying section is supplied with the feed into a flash drum. The liquid remaining in the flash drum is fed into the top of the stripping section. The vapor issuing from the top of the first HIDiC rectifying section is supplied as it is, into the bottom of the second HIDiC rectifying section, which has an overhead condenser giving an external reflux *R(2)* at the top. The liquid discharged from the bottom of the rectifying section is supplied into a flash drum. The vapor generated in the flash drum is transported with the vapor from the top of the second HIDiC stripping section to an overhead condenser whereas the liquid remaining in the flash drum is supplied into the top of the second HIDiC stripping section with the reflux liquid from the overhead condenser. The liquid produced by the condenser is supplied not only into the stripping section as the reflux but also into the top of the first HIDiC rectifying section as the external reflux *R(1)*.

Regarding the column structure for internal heat exchange, 1st through 34th stage of the first HIDiC rectifying section are respectively in thermal contact with the corresponding 1st through 34th stage of the first HIDiC stripping section and in the same manner the HIDiC column #2 is made up of the rectifying section having 2nd through 42nd stage in thermal contact with the stripping section having 1st through 41st stage.

Only for simplification, the capacity of internal heat exchange was assumed to be constant at each stage:

$U(i)A(i) = 800$ kcal/hr°C/stage (HIDiC column #1)

$U(i)A(i) = 400$ kcal/hr°C/stage (HIDiC column #2)

The inside diameter of the three columns of the existing C5-splitter is approximately of the order of 1 m. The plate spacing of the heat integrated system is assumed to be 300 mm. Judging from the experimental heat transfer observation made for a binary system of benzene-toluene (Noda et al. 2006), the order of the assumed *UA* value can be considered to be appropriate because the vapor flowrate in the second HIDiC rectifying section becomes half as much as that in the first HIDiC rectifying section..

4. Modeling and Governing Equations

Each section of the HIDiC system shown in Fig.4 can be treated as a single column except for taking into account the side heat exchangers between the rectifying and stripping sections.

The following governing equations can be obtained by modeling the HIDiC system

(Total mass balance) $F_i = D_i + W_i$

(Total mass balance of j-component) $F_i x_i(j,f) = D_i x_i(j,d) + W_i x_i(j,w)$

(Mass balance on k-stage of each section) $V_i(k+1) - V_i(k) + L_i(k-1) - L_i(k) = 0$

(Mass balance of j-component on k-stage of each section)

$V_i(k+1)y_i(j,k+1) - V_i(k)_i y_i(j,k) + L_i(k-1)x_i(j,k-1) - L_i(k)x_i(j,k) = 0$

(Enthalpy balance including internal heat exchange between the two sections)

$$V_i(k+1)H_{Vi}(k+1) - V_i(k)H_{Vi}(k) + L_i(k-1)H_{Li}(k-1) - L_i(k)H_{Li}(k)$$
$$+ Q_{ij}(m,k) = 0$$

(Heat transfer from i-stage of rectifying section to i-stage of stripping section)

$$Q_{ij}(m,k) = (-1)^{m-1} U_{ij}(k)A_{ij}(k)(T_j(k) - T_i(k))$$

where the tray temperature $T_1(k)$ indicates the stripping section and $T_2(k)$ the rectifying section.

The phase equilibrium of j-component is given by

$$y(j,k) = K(j,k)x(j,k)$$

The external reflux ratio is defined with the vapor flow rate $V_i(1)$ at the top of the second HIDiC rectifying section:

(Reflux ratio) $R_i = (V_i(1) - D_i)/D_i$

The reflux ratio of the first HIDiC rectifying section is defined using the top vapor flowrate V_{12} and the liquid flowrate L_{21} fed back from the condenser of the second HIDiC stripping section: $R_1 = L_{21}/(V_{12} - L_{21})$

5. Results and Discussion

5.1 Composition of the key component product by the HIDiC system

Pressure was specified at the top of the first HIDiC rectifying section to be $P_{1R} = 1.85$ atm. Pressure drop of both HIDiC columns was assumed as 0.003 atm/stage. Taking into account the pressure drop, the pressure of the second HIDiC rectifying section became $P_{2R} = 1.73$ atm at the top and the bottom pressure of the first rectifying section became 1.96 atm. This indicates the compression ratio $P_{1R}/P_{1S} = 1.96$ and $P_{2R}/P_{2S} = 1.85$.

Table 4 Simulation result of composition of the vapor from the top of the 1st HIDiC rectifying section and the bottom product from the 2nd HIDiC stripping section

Component Substance (mole %)	Vapor from the top of the 1st HIDiC rectifying section	Bottom product from the 2nd HIDiC stripping section
n-butane	0.0332	0.0000
i-pentane	1.9114	0.0000
n-pentane	21.9663	0.5998
2,2-dimethyl butane	0.4234	0.4612
c-pentane	75.2560	98.2700
2,3-dimethyl butane	0.1130	0.1789
2-methyl pentane	0.2954	0.4870
3-methyl pentane	0.0019	0.0033
n-hexane	0.0000	0.0001
methyl c-pentane	0.0000	0.0000
benzene	0.0000	0.0000
c-hexane	0.0000	0.0000
Flow Rate (kmol/h)	47.327	9.671

As a result of simulation made for the given separation specifications, the external reflux ratios of the both HIDiC columns were obtained to be *R(1)* = 2.60 for the first HIDiC rectifying section and *R(2)* = 5.58 for the second HIDiC rectifying section, respectively. In order to obtain pure c-pentane as the second bottom product, the vapor issuing from the top of the first HIDiC rectifying section should not contain the components less-volatile than c-pentane. As can be seen from Table 4, this condition is satisfied.

It has been confirmed that those external reflux ratios can give pure c-pentane as the second bottom product with the aid of the internal reflux effect by the internal heat integration.

5.2 Stagewise variation of flow rates of vapor and internal reflux liquid in the two HIDiC columns

Figures 6 and 7 show stagewise variation of internal heat exchange rate per stage, tray temperature and flow rates of vapor and internal reflux liquid. In these figures, only for convenience, the stages of both columns are numbered in the column height direction from the bottom. It can be seen that the temperature difference between the rectifying and stripping section becomes large as approaching the top for the first HIDiC column (see Fig.6). The temperature difference becomes large as approaching the bottom for the second HIDiC column (see Fig.7).

At the bottom of the first HIDiC column, the flow rates of vapor and liquid in the rectifying section (heat source) are large as compared to those in the stripping section (heat sink). The smallest values of the vapor flowrate obtained at the bottom of the stripping section and the top of the rectifying section, respectively, imply a great reduction of heat duties of the reboiler and overhead condenser.
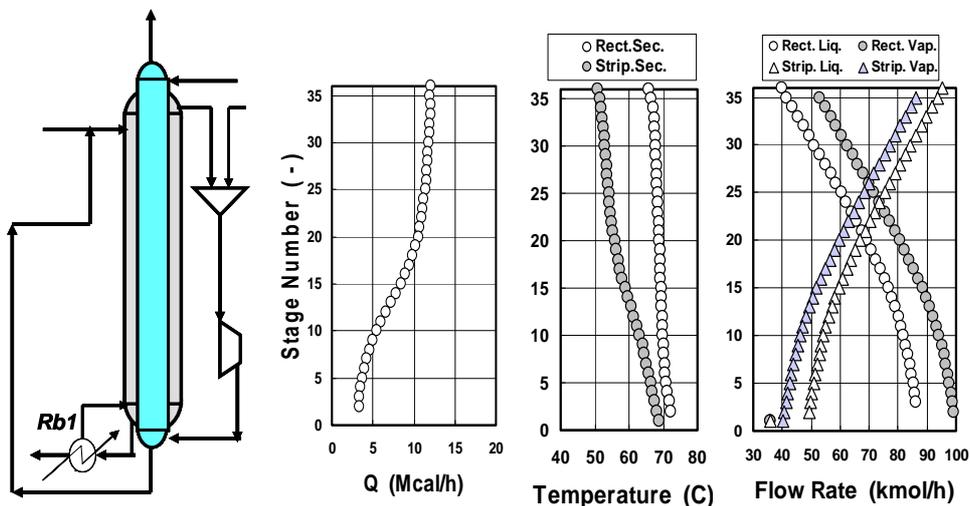
Fig.6 Stagewise variation of internal heat exchange rate, tray temperature and flow rates of vapor and internal reflux liquid in the first HIDiC rectifying and stripping sections
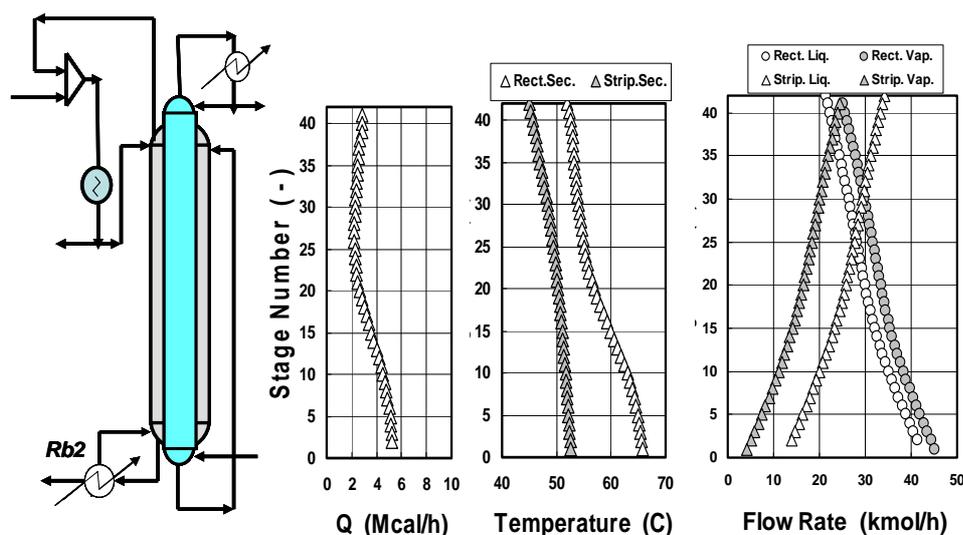
Fig.7 Stagewise variation of internal heat exchange rate, tray temperature
and flow rates of vapor and internal reflux liquid in the second HIDiC
rectifying and stripping sections

The same tendency can also be seen in the second HIDiC column. It can be
anticipated that the internal flow rates of vapor and liquid are considerably smaller for
the second HIDiC column than for the first HIDiC column. This suggests that the
second HIDiC column should have a heat transfer area small as compared to the first
HIDiC column. Therefore the overall heat transfer capacity *UA* of the second HIDiC
column was assumed to be half as large as that for the first HIDiC column. It has been
found that the internal heat exchange rates in the second HIDiC column become much
less than half of those in the first HIDiC column. This is due to the fact that the
second HIDiC column is also operated at the compression ratio smaller than the first
HIDiC column.

According to the vapor and liquid flow rates controlled by the internal heat exchange,
for example, the stagewise variation of the vapor and liquid flow in the first HIDiC
column clearly indicates additional increase in the internal reflux liquid due to the
condensation in the rectifying section and the correspondent increase in the internal
vapor flow due to the vaporization in the stripping section.

5.3 Effect of heat integration on fractional distillation

Figures 8 and 9 show stagewise variation of concentration of c-pentane in the first and
second HIDiC columns, respectively. Cyclopentane plays as one of the more-volatile
components in both the rectifying and stripping sections of the first HIDiC column
but in the second HIDiC column, it plays as the less-volatile component. It can be
seen from Fig.8 that c-pentane is forced not to go downward in the first HIDiC
stripping section.

Owing to the multi-component system, however, there occurs an accumulation of
intermediate key component in the first HIDiC rectifying section, where the
separation specifications can be achieved by cutting sharply the mixture between c-
pentane and 2,3-dimethyl butane (see Table 4).
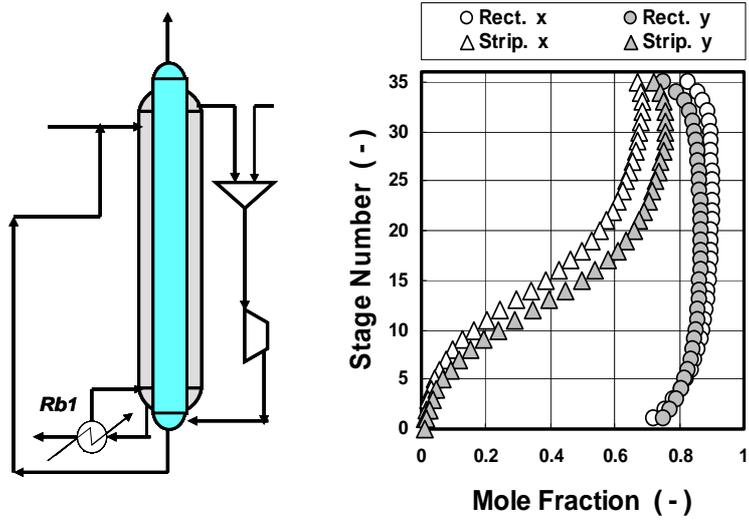
Fig.8 Stagewise variation of c-pentane concentration in the rectifying and stripping sections of the first HIDiC column:
y, x: mole fraction of c-pentane in vapor and liquid, respectively.
$(P_{1R}/P_{1S} = 1.96$ and $R(1) = 2.60)$
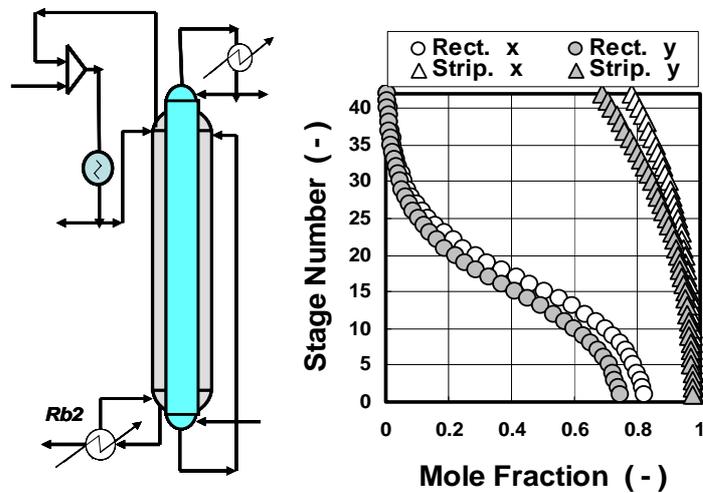
Fig.9 Stagewise variation of c-pentane concentration in the rectifying and stripping sections of the second HIDiC column:
y, x: mole fraction of c-pentane in vapor and liquid, respectively.
$(P_2/P_1 = 1.73$ and $R(2) = 5.58)$

As far as these simulation results are concerned, it is clear that the second HIDiC column produces pure c-pentane as the bottom product of the stripping section and the overhead product containing the remaining components more-volatile than c-pentane.

It should be kept in mind that these successful results stand on the assumption of ideal stage with a constant overall heat transfer coefficient.

5.4 Energy saving analysis of the new HIDiC system for process intensification

The main purpose of the HIDiC process intensification is to reduce the energy consumption of the reboilers of the C5-splitter without loosening the separation specifications. Although the matter of the utility such as cooling water is very important, the energy withdrawn from the overhead condenser can be outside the evaluation of energy-saving rate. The rate of energy saving attained by the HIDiC method can be defined as

$$ES = 1 - \frac{E_{HIC}}{E_{ST}}$$

where E_{ST} is the total energy consumed by the three reboilers of the existing C5-splitter, which was estimated from the operation data of heat and mass balance. The total energy consumption E_{HIC} of the HIDiC system is evaluated as the total of the energy consumed by the two reboilers and the energy consumption calculated from the shaft work of one compressor (see Fig.5). The HIDiC system is equipped with a small preheater for assuring the compressor of stable adiabatic compression without generating dews.

From a viewpoint of the reduction of carbon dioxide emission, the electric energy consumed by the compressor should have been estimated taking into account the efficiency of thermal power plants. In this research project, the efficiency of thermal power plants was assumed as 35%.

The result of energy-saving analysis is shown in Table 5.

Table 5 Energy-saving analysis

HIDiC column	Section	Theoret. Stages	Feed Stage	Reflux Ratio	Reboiler Heat Duty (Gcal/h)	Compressor Shaft Work (Gcal/h)	Compressor Energy Consumption (Gcal/h)** Eff.=35%
HIDiC column #1	Strip.	35	#1		0.2720		
	Rectify	35	#35	2.60	0.0126*	0.0540	0.1543
HIDiC column #2	Strip.	42	#1		0.0276		
	Rectify	42	#42	5.58			
		Total energy consumption (Gcal/h)				0.3662	0.4665***
		Energy-saving rate (%)				67.2	58.3

* Heat duty of the preheater E_{prc} installed before the compressor
** The efficiency of power plants is assumed to be 35% from the statistical data of thermal power generating efficiency.
*** Since the existing C5-splitter has the same size feed preheater as the new HIDiC system, the heat duty of the preheater for feeding estimated as 0.00394 Gcal/h can be neglected in common in the analysis of energy consumption for both the systems: the existing C5-splitter and the HIDiC system under consideration.

The total energy consumption is given by

$$E_{ST} = E_{S1} + E_{S2} + E_{S3} \qquad \text{for the existing C5-splitter}$$

$$E_{HIC} = E_{H1} + E_{H2} + E_{prc} + E_{com}$$ for the HIDiC system

where E_{S1}, E_{S2}, E_{S3} are the heat duty of each reboiler of the C5-splitter, E_{H1} and E_{H2} the heat duty of each reboiler of the HIDiC system and E_{com} the energy consumption by the compressor taking into consideration the power generating efficiency.

In this analysis, the following result has been obtained:

$$E_{ST} = 1.1179 \quad \text{Gcal/h and} \quad E_{HIC} = 0.4665 \quad \text{Gcal/h}$$

The rate of energy-saving to be achieved by this HIDiC system is given by

$$Es = (1 - \frac{0.4665}{1.1179}) \times 100 = 58.3 \%$$

This result suggests that a very large energy-saving effect can be attained by the new HIDiC system. It is another great advantage that the new HIDiC system consisting of two HIDiC columns requires only one compressor.

6. Concluding Remarks

It has been ascertained that a great rate of energy-saving can be attained by the internal heat integration method. A great rate of energy saving around 58.3 % of the total energy consumption of the three reboilers of the existing C5-splitter can be attained with the new HIDiC system consisting of two HIDiC columns, the first one of which is equipped with one compressor. This idea suggests a new important concept that if a pressurized vapor mixture issuing from the top of the upstream rectifying section is supplied as it is, into the bottom of the rectifying section of the next downstream HIDiC column in a fashion of cascade connection, a very profitable HIDiC system can be constituted without installing any compressor. It may be concluded that if this kind of internal heat integration methods are applied to many columns of various distillation plants in chemical industry, a great contribution of process intensification can be realized. How to promote widely these energy saving methods leading to a great reduction of carbon dioxide emission should be a very important issue as a key technology for prevention against global warming.

Acknowledgment

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