ENERGY-SAVING CHARACTERISTICS OF HEAT INTEGRATED DISTILLATION COLUMN TECHNOLOGY APPLIED TO MULTI-COMPONENT PETROLEUM DISTILLATION

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This is an experimental and analytical report of the second-phase national research project of energy-saving heat integrated distillation column (HIDiC) technology applied to multi-component hydrocarbon distillation processes downstream of the naphtha cracking process. The first column of an existent commercial-scale distillation plant extracting cyclopentane from multi-component hydrocarbon mixtures was selected as the model column of the HIDiC project. The actual operation data were employed not only for the specification of distillation system design but also for the energy-saving analysis. A commercial-scale HIDiC pilot plant has been constructed based on the computer-aided HIDiC design of system and operation. A comparison of the test operation data was made with the computer simulation taking into account the power consumption of the compressor installed between the rectifying and stripping sections. It has been confirmed that the energy conservation level better than the design specification can be attained by means of the actual internal heat integration of the HIDiC pilot plant. The target of energy saving more than 50% of the energy consumption of the existent conventional distillation column (model column) was achieved in various operation conditions. The energy saving higher than 76% was achieved under the condition when the external reflux ratio was reduced to zero. The stable continuous HIDiC operation for 1,000 hr has successfully been realized by the pilot plant.

KEYWORDS: heat integrated distillation column, energy-saving, distillation, packed column

INTRODUCTION

The study of HIDiC process system engineering has been progressing mainly with respect to a packed-column-type HIDiC system (Takamatsu *et al.* 1988). The purpose of this national project dealing with a double-tube-type packed column HIDiC system is to construct a generalized design method as well as to practically test a commercial-scale HIDiC system following the first-phase project. This paper reports how a commercial scale HIDiC pilot plant was constructed based on the computer-aided simulation method (Horiuchi *et al.* (2005)). It has also been shown by the same simulation method that satisfactory results can be attained by the pilot plant test operation.

DESIGN SPECIFICATION

BASIC FLOW CONFIGURATION OF HIDiC SYSTEMS

The basic flow diagram of the HIDiC pilot plant, constructed in January 2005, is shown in Figure 1. The hydrocarbon mixture comprising 12 components is fed to the top of the stripping section which is operated at normal pressure. The internal reflux (liquid) flowing down in the stripping section is enriched with less-volatile components and its flow rate decreases due to additional evaporation by heat input from each stage of the rectifying section pressurized by a compressor. The vapor arriving at the top of the stripping section is compressed into the bottom of the rectifying section. The vapor flowing upward in the rectifying section is enriched with more-volatile components and its flow rate decreases due to additional condensation. The latent heat released by condensation is transferred across the column wall into the stripping section for the additional evaporation.

The vapor arriving at the top of the rectifying section is condensed with the overhead condenser and drawn out as the lighter component product. The quantity of the condensate used for the (external) reflux can be made considerably small in the case of HIDiC system. The internal reflux arriving at the bottom of the rectifying section is

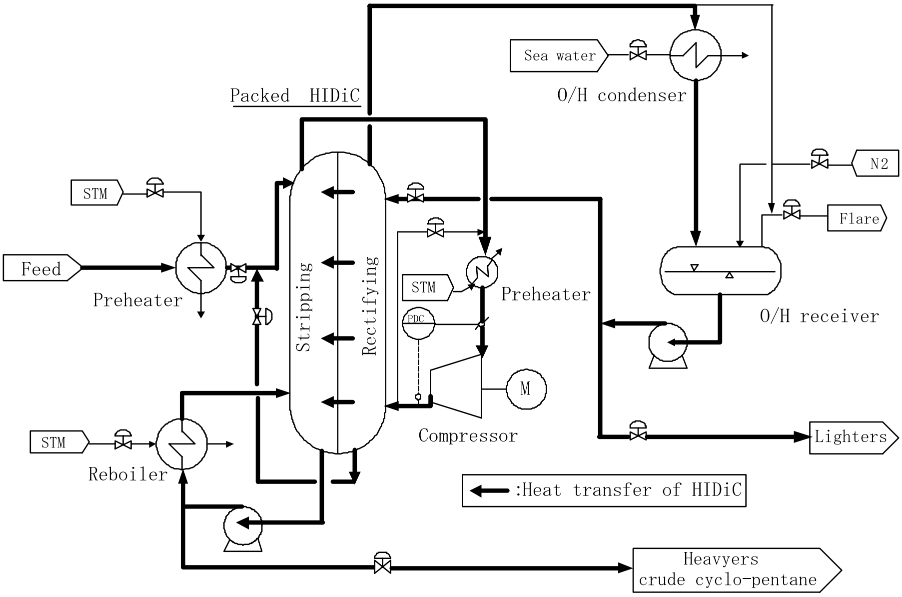


Figure 1. Flow diagram of HIDiC pilot plant

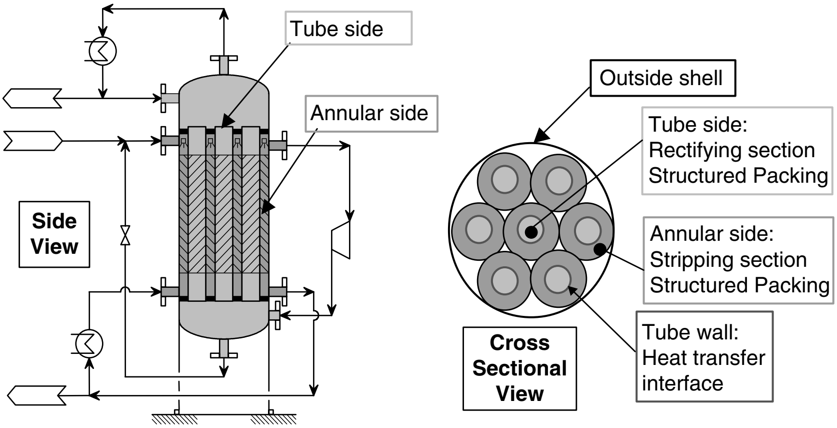


Figure 2. Structure of the HIDiC pilot plant

supplied as the reflux to the top of the stripping section. The heavier component mixture including cyclopentane is obtained as the bottom product of the stripping section. The heat duty for the reboiler can be reduced due to the additional evaporation of the internal reflux by the internal heat integration. In the actual plant, the first column (model column) is followed by two more distillation columns to obtain pure cyclopentane.

STRUCTURE OF THE HIDiC SYSTEM

As shown in Figure 2, the outside shell of the constructed HIDiC pilot plant having 1.4 m in diameter and 27 m in height has seven double-tube packed column units accommodated inside. Each inner tube side serves the rectifying section while each annular side serves the stripping section. The number of theoretical stages of each section is 35.

OPERATION DATA

BASIC MATERIAL BALANCE IN DISTILLATION OF 12 COMPONENTS MIXTURES

Table 1 indicates an actual separation result of the overhead and bottom products obtained by the pilot plant. Figure 3 is a photograph of the pilot plant, constructed in February 2005.

COMPUTER SIMULATION

BASIC EQUATIONS

a) Phase equilibrium equation
   The state equation of Peng and Robinson (1976) is applied with an assumption of ideal solution.
b) Column model and calculation algorism

Table 1. Flow rates of components in the operation of pilot plant

Components	Feed	Over head products	Bottom products
n-butane	0.04	0.27	0.00
i-pentane	1.21	9.95	0.00
n-pentane	10.76	85.57	0.22 *2)
2,2-dimethylbutane	0.38	0.07 *1)	0.45 *2)
cyclo-pentane	39.77	4.11 *1)	43.98
2,3-dimethyl-butane	2.02		2.35
2-methyl-pentane	17.05		19.54
3-methyl-pentane	6.44		7.47
n-hexane	11.47		13.26
methyl-cyclo-pentane	10.42		12.13
benzene	0.08		0.10
cyclo-hexane	0.36		0.45
total (wt%)	100.00	100.00	100.00
flow rate (kg/h)	1,900.0	238	1,662.0
flow rate (kgmol/h)	24.60	3.20	21.40

Target condition

*1) specified the cyclo-pentane (abbreviation c.p.) in over head products is 5.0 wt% in total

*2) specified that n-pentane & 2,2-dimethylbutane in bottom products are 0.5 wt% in total

The simulation analysis is made with the algorism of inside/out (Boston and Salivan (1974)) by use of Pro/2 simulation software of INVENSYS (Russell, (1983)).

CONDITIONS AND ASSUMPTION

a) Material balance
The material balance with respect to the feed and the bottom and overhead products is the same as the operating data (Table 1) of the pilot plant.

b) Number of theoretical stages
The number of theoretical stages of each column (35 stages) is the same as that of the pilot plant design.

c) Pressure drop in both columns
Pressure drop from the bottom to the top in packed column is the same as the operation data (0.0102 kg/cm^2).

d) Compression ratio in compressor
Compression ratio (1.86) is fixed to be the same as operation data.

e) Reflux ratio
The reflux ratio for simulation is approached 0.0034 as an approximation of zero reflux ratio of the pilot plant.

f) Heat transfer from the rectifying to the stripping section

Figure 3. Pilot plant

The heat transfer rate is defined by $Qj = UAdT$
Where ***U***:Overall coefficient of heat transfer between the rectifying and stripping sections
A:Heat transfer area on each theoretical stage.
dT:Temperature difference between the stripping and rectifying sections at theoretical j-stage.
At each theoretical stage, ***UA*** was assumed to be 800 Kcal/hr/deg. or 930 W/K as pilot plant design specification but for the simulation, ***UA*** had to be chosen 1298 Kcal/hr/deg or 1509 W/K to obtain a converged solution.

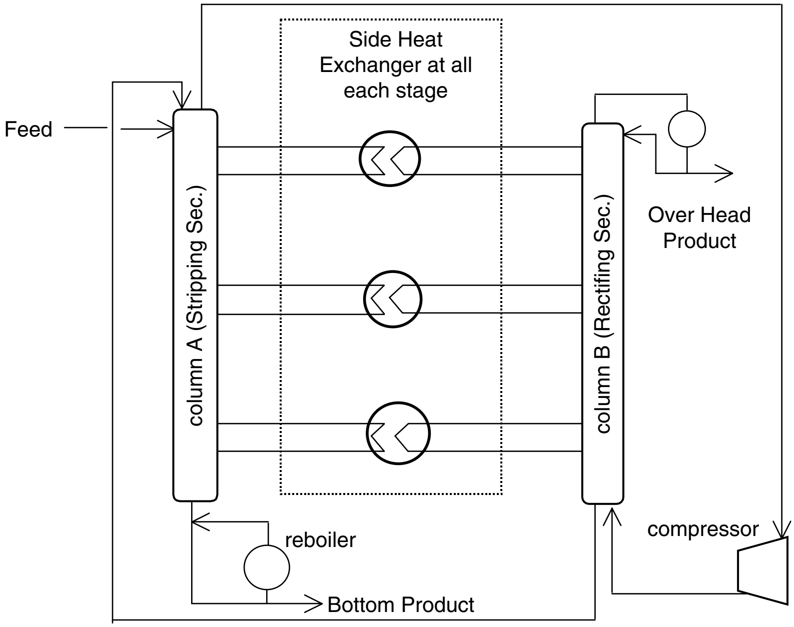


Figure 4. Imaginary flow configuration for computer simulation

IMAGINARY FLOW CONFIGURATION FOR COMPUTER SIMULATION

As shown in Figure 4, the basic flow configuration of HIDiC system was altered to a twin column type model having separately a rectifying column and a stripping column only for computer simulation. An imaginary heat exchanger was installed on each couple of stages matched between the rectifying and stripping columns. This flow configuration is the same as the configuration used for design and construction of the pilot plant (Horiuchi *et al.*, (2005)).

RESULT

SIMULATION RESULT AND OPERATION DATA

The results of simulation and actual operation record are given in Table 2, where the energy duty and operation condition are compared between the computer simulation and operation data of the pilot plant. The column (A) indicates the simulation result of HIDiC system obtained when the external reflux approaches 0.0034. The column (B) indicates the actual operation result of HIDiC pilot plant with zero external reflux.

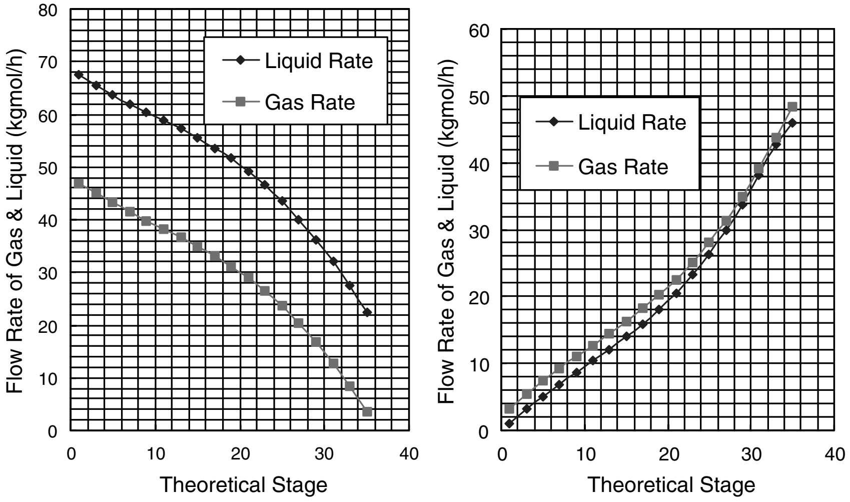
This operation of zero reflux ratio can be achieved only by HIDiC systems, because the internal reflux increases due to the additional condensation in the rectifying section. Figure 5 shows the simulation result of internal flow rate of the rectifying and stripping section in the case of column (A).

Table 2. Comparison of simulation result with operation data

			(A) simulation result of HIDiC		(B) operation result of HIDiC
a)	Material balance	wt%	same as Table 1	*1	same as Table 1
b)	Mumber of theoretical stage of both column	(R.sec/S.sec)	35/35	*1	35/35
c)	Differential pressure of columns	(R.sec/S.sec) kg/cm^2	0.0102/0.0102	*1	0.0102/0.0102
d)	Compession ratio of compressor		1.86	*1	1.86
e)	External reflux ratio		0.0034	*1	0
f)	***UA***: heat transfer of HIDiC	kcal/hr/deg/stage	**1298**	*1	******
g)	Feed preheater load	Mcal/hr	8	*2	7.9
h)	Compressor preheater load	Mcal/hr	10.2	*2	4.1
i)	Reboiler load	Mcal/hr	7.1	*2	13.1
j)	Compressor load	Mcal/hr	32.8	*2	31
k)	**Total load**	Mcal/hr	**58.1**		**56.1**

*1: input data

*2: output data



Stripping Sec. Rectifying Sec.

Figure 5. Simulation result of internal flow rates inside the tube units

ESTIMATION OF OVERALL COEFFICIENT OF HEAT TRANSFER

The simulation result (A) indicates good coincidence with the actual operation data (B) in Table 2. Regarding the heat transfer coefficient, $\boldsymbol{U}$ ($U = Q/AdT$), the numerical value of $\boldsymbol{Q}$ and $\boldsymbol{dT}$ on the each stage could not be measured directly in the operation of the plant. The heat transfer capacity $\boldsymbol{UA}$ can be estimated only from the parameter-fitting method of simulation of (A) in Table 2. The converged solution was obtained only at the value (1298) of $\boldsymbol{UA}$, shown at (A) in Table 2. This $\boldsymbol{UA}$ is considerably better than the design specification (800 Kcal/hr/deg.).

Since the heat transfer area A per each theoretical stage of HIDiC pilot plant is 2.25 m^2, the overall coefficient of heat transfer $\boldsymbol{U}$ is 577 Kcal/m^2/hr/deg. It can be conjectured from this good result that the heat-transfer walls both on the rectifying and stripping sides were kept sufficiently wet, and the flow of vapor and liquid inside the seven double-tube packed column units was substantially uniform.

ENERGY SAVING OF HIDiC PILOT PLANT

a) Definition of energy saving evaluation

The reboiler load necessary at the minimum reflux ratio (R/R = 8.6) of the conventional column (model column) was adopted as the standard energy duty for comparison. This standard energy duty (241 Mcal/hr) was obtained in the same condition as the material and energy balance in Table 1, where the condition of minimum reflux ratio corresponds to the number of theoretical stages = 160.

On the other hand, the total energy duty of the HIDiC system is the total of the preheater load, the reboiler load and the power consumption of the compressor.

The following defining equation is adopted for energy saving evaluation:

$$\begin{aligned}\text{Standard energy duty} &= (\text{reboiler load in conventional column}\\ &\qquad \text{at minimum reflux ratio})\\ \text{Energy duty of HIDiC} &= (\text{Preheater load}) + (\text{reboiler load})\\ &\quad + (\text{compressor power})\\ \text{Energy saving rate (\%)} &= \{1 - (\text{energy duty of HIDiC pilot plant})/\\ &\qquad (\text{standard energy duty})\} \times 100\end{aligned}$$

b) Result of energy saving evaluation

$$\text{Energy saving rate (\%)} = \{1 - (56.1)/(241)\} \times 100 = 76.7$$

It should be noticed that the highest result of energy-saving rate 76.7% can be obtained only with the HIDiC system in the operation condition when the external reflux ratio is approached zero.

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