Heat Integration of Distillation Column

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For heat integration performance of distillation column, CC (Conventional Column),
VRC (Vapor Recompression Column), HIDiC (Heat Integrated Distillation Column)
and DDC (Diabatic Distillation Column) have been evaluated by using C_5 fraction
separation. DDC was superior to another heat integration technology, surprisingly VRC
was superior to HIDiC. Entropy production rate was evaluated for the above various
heat integration systems and concluded why VRC was superior to HIDiC.

1. Introduction

Japanese refinery and chemical industries consumed 33.2 million kL oil per annum,
40% demand is needed to operate distillation columns. As a result, this urges the
industries to continuously develop some advanced technologies for heat integration in
distillation process. This is not only for cost reduction, but also for reducing the CO_2
emissions. In the development history of heat integration in distillation process, Petlyuk
et al. (1965) introduced the thermally coupled prefractionator for three-product mixture
separation. VRC is also one of the efficient methods for saving energy first suggested
by Robinson and Gilliland (1950). Mah et al. (1977) proposed the concept of SRV
(Secondary Reflux and Vaporization) based on the heat exchange between the rectifying
and stripping sections to have better thermal efficiency. A group of Japanese researchers
(Nakaiwa et al. 2000) further studied the VRC and SRV, eventually evolved a new
theory, namely HIDiC technology. It combines the advantages of both vapor
recompression and diabatic operation and can give significantly lower energy demands.
For this reason, there are many HIDiC researches carrying out recently, for example the
distillation of close-boiling mixtures, such as propylene–propane and ethylbenzene–
styrene systems. Olujic et al. (2003) studied HIDiC for these two systems and proposed
that up to 80% energy saving is expected. These results illustrate that HIDiC is
thermodynamically excellent. The technology has been established in Japan for C_5
fraction by Horiuchi et al. (2006). Prior to focusing on HIDiC the above heat integrated
distillation column systems have to be evaluated based on standard separation
components. On the contrary to the above application of heat integrated distillation
column to industrial scale, Schaller et al. (2001) proposed numerically optimized
analysis of DDC compared with CC. Jimenez et al. (2004) proposed an optimization
approach with sequential heat exchangers. In this paper the performance of heat

integration for the above heat integrated columns including DDC was evaluated by the analysis for heating and cooling duties, stage-by-stage entropy production rate, liquid and vapor flow and temperature profile based on C_5 fraction separation.

2. Energy Saving Performance

C_5 fraction comes from naphtha cracker is described at Table 1. The separation performance on HIDiC pilot plant was reported by Horiuchi et al. (2006). Not only HIDiC but also VRC and CC was studied as described in Table 1 and Fig. 1(a),(b), (c) through simulation study by Aspen plus 2006. Peng-Robinson method was specified for physical property estimation on vapour liquid equilibrium and enthalpy. Simulation results was enough accurate on composition of top and bottom as described in Table 1 for evaluating energy saving performance in various heat integrated columns.

Table 1 C_5 fraction and separation performance

	Component	Feed	Top				Bottom			
			Pilot Plant	Simulation			Pilot Plant	Simulation		
			HIDiC	HIDiC	VRC	CC	HIDiC	HIDiC	VRC	CC
1	2-Methyl-butane	0.03	0.1	0.1	0.1	0.1	0	0	0	0
2	n-Pentane	0.38	1.2	1	1	1	0	0	0	0
3	2.2-Dimethyl-butane	0.53	1.29	1.3	1.4	1.4	0.14	0.1	0	0
4	Cyclopentane	41.23	96.41	96.4	96.4	96.4	10.38	9.1	9.1	9.1
5	2,3-Dimethyl-butane	2.49	0.56	0.4	0.4	0.4	3.6	3.7	3.7	3.7
6	2-Methyl-pentane	20.66	0.44	0.8	0.8	0.8	31.37	32.2	32.2	32.2
7	3-Methyl-pentane	7.89					12.26	12.5	12.5	12.5
8	n-Hexane	13.75					21.47	21.8	21.8	21.8
9	Methyl-cyclopentane	12.57					19.98	19.9	19.9	19.9
10	Benzene	0.07					0.14	0.1	0.1	0.1
11	Cyclohexane	0.4					0.64	0.6	0.6	0.6
	total(w%)	100	100				100			
	Flow Rate kg/h	1,500	552				948			

Operating condition is described in Fig.1 (a) CC, (b) VRC, (C) HIDiC. CC was studied as base case for comparing on energy saving degree of performance. The theoretical stage number 40 including condenser was evaluated to satisfy the separation based on the reflux ratio 13.8. In VRC, top vapor stream was divided , 90 % of the flow rate was introduced to compressor for supplying enough heat flow to the reboiler. Required power was 63.5 kW with compression ratio 1.83 to keep practical approach temperature as heat source for the reboiler. The theoretical stage number 39 and the reflux ratio 10.8 was evaluated to satisfy the same separation as in CC.
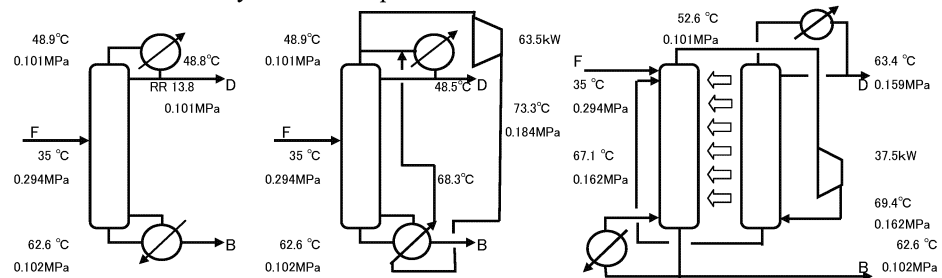

Fig.1 (a) CC   *Fig.1 (b) VRC*   *Fig.1 (c) HIDiC*

In HIDiC, the column was divided between rectifying section and stripping section, top vapor stream was introduced to the compressor for supplying enough heat flow to

stripping section from rectifying section , the exit stream of compressor was introduced to the bottom of rectifying section and consequently heat transfer from rectifying section to stripping section was possible. Required compressor power was 37.5 kW with compression ratio 1.6 to keep practical approach temperature difference between rectifying section and stripping section as heat source. The theoretical stage number for the rectifying section was 35 and also 35 for the stripping section as described by Horiuchi et al.(2006). The reflux ratio 3.7 was specified. Heat transfer rate from rectifying section to stripping section was defined. In HIDiC simulation, 800～1600 of UA was studied for getting optimum value from energy saving viewpoint.

$$Q_n = UA(T_{Rn} - T_{Sn}) \tag{1}$$

where Q_n: Heat transfer rate k J / h , U: Over all heat transfer coefficient W / (m$^2 \cdot$ K)

A: Heat transfer area m^2 ,T_{Rn} : n-th stage temperature at rectifying section ℃

T_{Sn}: n-th stage temperature at stripping section ℃

Energy saving performance for CC, HIDiC and VRC was summarized in Table 2.
VRC was superior to HIDiC. It was surprising enough because HIDiC concept was based on DDC which uses a heat exchanger at each stage of the column and reduces the exergy needed to perform the separation .

Table 2 Energy saving performance for CC,HIDiC and VRC

Operation Parameter		CC	HIDiC	VRC
UA	W/K		929	
Split Ratio	−			0.90
QB	GJ/h	3.18	0.92	0.17
Power	GJ/h		0.13	0.23
Energy Saving	%	100	59.37	71.92

QB: Reboiler duty
Split Ratio: Top vapor split ratio to compressor
Power: Required compressor power
Energy Saving:
　　((QB in CC) − (QB + Power/0.351)) x100 /(QB in CC)
　　0.351 : Efficiency of Electricity to Power Generatioin

3. Analysis of individual heat integration system

Instead of just one heating source for the reboiler and one cooling source for the condenser, DDC uses a heat exchanger at each stage as described in Fig. 2 by Jimenz et al. (2004). Spreading out the heating duties of the reboiler and the cooling duties of the condenser implies potential savings because the reboiler is adding heat at a higher temperature than needed and the condenser is removing heat at a lower temperature.

3.1 Heat duty profile
Heat transfer rate at the each stage of the column was plotted in Fig. 3. Only reboiler duty 3.207 GJ/h and condenser duty -3.138 GJ/hr was plotted for CC, reboiler duty 0.166 GJ/h and the duty 2.723 GJ/h supplied by compressor exit stream as heat source was plotted for VRC, in which not plotted for for condenser duty because of heat source of the reboiler. Each stage heat duty 0.249 GJ/h below the feed stage was specified for heating in case of DDC as described in Fig. 3, each stage heat duty -0.249 GJ/h above
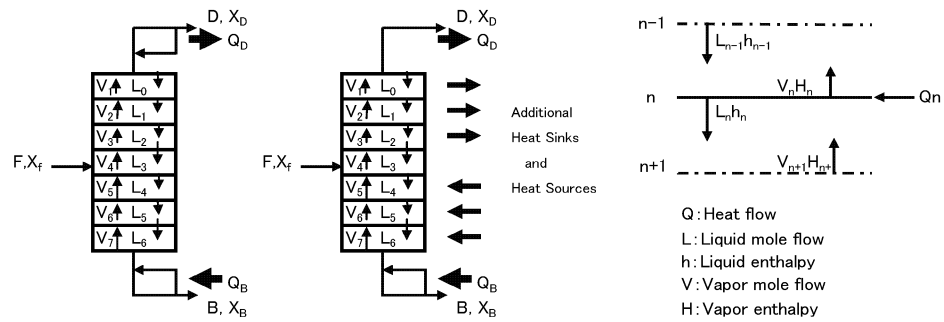
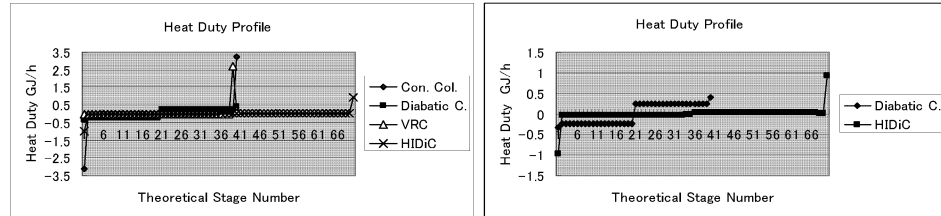*Fig.2 C C, DDC with additional heat exchange and Variables around stage n*

Fig.3 Heat duty profile for CC, DDC,VRC and HIDiC

the feed stage was specified for cooling. Aa a result of applying interheaters and intercoolers to the column, the reboiler duty was 0.401 GJ/h and the condenser duty 0.332 GJ/h. Heat transfer rate at each stage for HIDiC was -0.0366 GJ/h at the top stage of rectifying section for cooling and -0.0195 GJ/h at the bottom stage . The each stage of stripping section was heated by the heat transfer rate from the rectifying section. The reboiler duty was 0.92 GJ/hr and the condenser duty was 0.97 GJ/h.

3.2 Liquid flow and Vapor flow profile

 Liquid and vapor flow rates for DDC linearly increased from top stage to feed stage because of internal reflux increasing due to intercooler at each stage, decreased to bottom stage and were remarkably lower than those of the CC except feed location zone as described in Fig. 4 and Fig. 5. The significance of lower flow rates is that the column
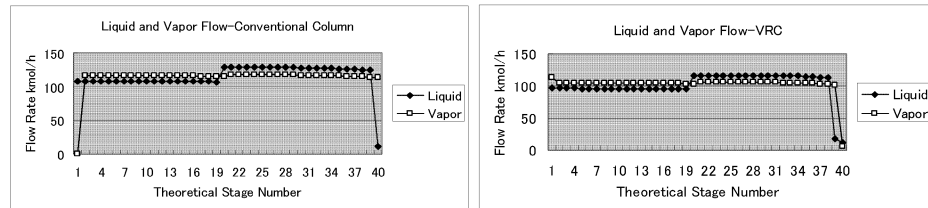

Fig.4 Liquid and Vapor flow profile for CC and VRC

allows cross sectional area for the heat exchangers to be installed without interfering with the material flow in the column, implying that CC could be retrofitted with the
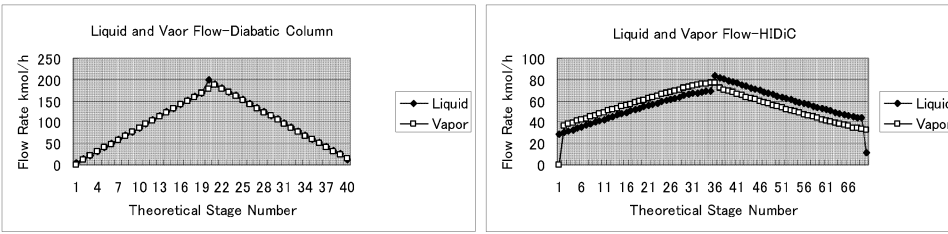
Fig.5 Liquid and Vapor flow profile for DDC and HIDiC

heat exchangers without adverse effect.

3.3 Temperature Profile

In Fig. 6, as for diabatic column the stage temperatures vary almost linearly along the column, indicating that each stage is doing its share of the separation process. The conventional column has very little temperature change across stages 21-30. HIDiC was similar to DDC due to same liquid and vapor flow rate profile.
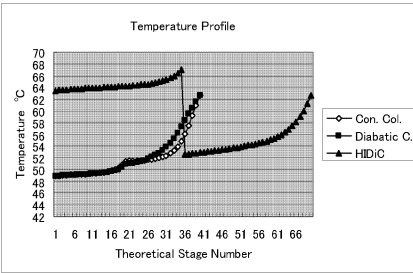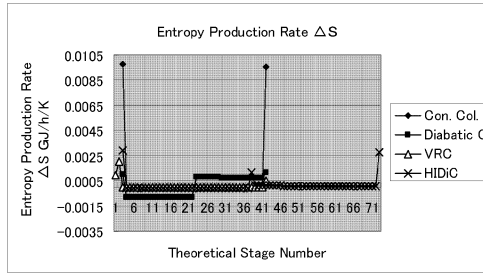

Fig.6 Temperature profile   *Fig.7 Entropy Production Rate*

3.4 Entropy production rate

Vapor coming up from stage n+1 and liquid flowing down from stage n have to balance the distillate D above the feed and the bottoms B below the feed, respectively as described in Fig.2 . In order to calculate the heat required at each stage to maintain the desired temperature profile, the energy balance has to be maintained for each stage n:

$$Q_n = V_n H_n + L_n h_n - V_{n+1} H_{n+1} - L_{n-1} h_{n-1} \qquad (2)$$

Schaller et al. (2001) expressed the entropy production rate as:

$$\triangle S = \Sigma Q_n / T_n \quad (n=0, \cdots, N) \qquad (3)$$

The heat source temperature for the Q_n is to be equal to the stage temperature T_n .
Exergy loss is equivalent to entropy production rate. Note in Fig. 7 and Table 3 that the total entropy production rate is significantly lower in DDC. At the condenser (stage 0) , it is observed that the entropy production rate in CC's condenser is approximately 10

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Table 3 Entropy Production Rate

Column	ΔS GJ/(h·K)	Nt
CC	0.01930	40
DDC	0.00200	40
VRC	0.00347	40
HIDiC	0.00691	70

Nt: Theoretical stage number

times as large as the corresponding entropy production rate in DDC. It is also observed that the entropy production rate in CC's reboiler (stage 40) is 8 times larger than the entropy production rate of DDC's reboiler. The entropy production rate in VRC was superior to HIDiC which was similar concept as DDC.

4. Conclusion

Energy saving performance for various heat integrated distillation systems in case of applying to C5 fraction was evaluated through the analysis of column internal variables and entropy production rate. DDC which was ideal heat integrated distillation system was superior to another systems , so heat integration with intercooler and interheater could be practically used. VRC was superior to HIDiC, which was considered on the way for optimum due to heat transfer rate constraint compared to DDC. Separation performance around feed location was sharp for DDC and HIDiC due to more internal flow rate than CC.

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