DYNAMICS AND CONTROL OF HEAT INTEGRATED DISTILLATION COLUMN (HIDIC)

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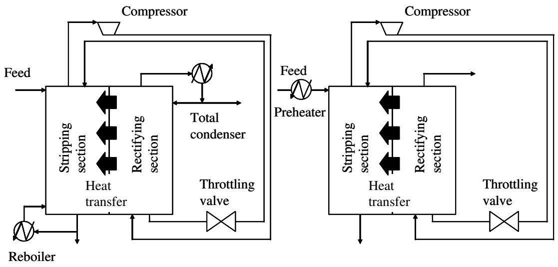
Abstract: A heat integrated distillation column (HIDiC) is a new and highly energy-efficient distillation process. In this work, dynamic simulation models for several types of HIDiCs were developed. The dynamics and controllability of HIDiCs were investigated and compared with those of a conventional distillation column (CDiC). HIDiC has a more complex structure and slower dynamics than CDiC. However, the control performance of HIDiC is comparable to that of CDiC as far as a suitable control system is designed. In addition, an industrial HIDiC plant in Japan was rigorously modeled, and its dynamics and control issues are discussed.

Keywords: Heat integrated distillation column, Energy saving, Process control, Dynamics, Controllability

1. INTRODUCTION

As global warming becomes a more serious problem, the demand to suppress the exhaust of greenhouse gas has increased and technology development to achieve energy saving in industries has been promoted. Since distillation is the most widely-used separation process, quite energy-intensive, and accounts for a large part of energy consumption in industries, the development of an energy-efficient distillation process is crucial.

A heat integrated distillation column (HIDiC) is an energy-efficient distillation column, that has the potential for drastic reduction of energy consumption (Takamatsu et al., 1996). The basic concept of HIDiC is that heat duty needed in a reboiler and a condenser can be reduced simultaneously by enhancing internal heat integration. In the last decade or so, basic characteristics and energy savings of HIDiC have been investigated vigorously. These researches include exergy-based analysis of energy savings of ideal HIDiC (Takamatsu et al., 1997), analysis of energy savings in a multicomponent separation process (Iwakabe et al., 2004), and detailed design in which material transfer rate, heat transfer rate, and pressure drop are taken into account (Noda et al., 2004). In addition, an industrial HIDiC plant has been built and operated to prove its usefulness and also to investigate practical issues. However, past research on HIDiC has focused mainly on its static characteristics. Little research on the dynamics and controllability of HIDiC has been carried out, while internal heat integration and a complex structure of HIDiC might make its operation more difficult than conventional distillation columns. In particular, a new control scheme must be developed for ideal HIDiC, because it does not have both a reboiler and a condenser and thus reflux flow rate and



(a) HIDiC (b) ideal HIDiC

Fig. 1. Schematic diagrams of HIDiCs.

reboiler heat duty cannot be used as manipulated variables.

For practical applications of HIDiC, its controllability needs to be investigated and an appropriate control system needs to be developed. In the present work, a dynamic simulator for HIDiC and ideal HIDiC is developed. By using the developed simulator, static characteristics, especially energy savings, of HIDiCs are investigated, and various multiloop control structures have been studied to clarify a control strategy suitable for HIDiCs. In addition, an industrial HIDiC plant in Japan was rigorously modeled, and its dynamics and control issues are discussed.

2. DYNAMIC MODEL OF HIDIC

In this section, the structures of HIDiC and ideal HIDiC are shown and the developed dynamic models are briefly described.

2.1 Structure of HIDiC

A schematic diagram of HIDiC is shown in Fig. 1(a). HIDiC has a compressor and a throttling valve between the bottom of the rectifying section and the top of the stripping section. Vapor rising from the top of the stripping section is pressurized by the compressor and supplied to the bottom of the rectifying section. Liquid flowing from the bottom of the rectifying section is supplied to the top of the stripping section through a throttling valve. The feed is supplied to the top of the stripping section.

In a conventional column, heat is transferred by a reboiler and a condenser. In HIDiC, on the other hand, the rectifying section and the stripping section are in physical contact, and the pressure in the rectifying section is kept higher than that in the stripping section by using a compressor to enhance heat transfer from the rectifying section to the stripping section through the wall. By this internal heat transfer, vapor in the rectifying section condenses and liquid in the stripping section evaporates. As a result, the heat duty needed in the reboiler and the condenser can be reduced and high energy saving can be achieved. Although a compressor is required in HIDiC, energy consumption by the compressor is less than that reduced in both the reboiler and the condenser. Therefore, HIDiC is more energy-efficient than conventional distillation columns.

Fig. 1(b) shows a schematic diagram of an ideal HIDiC (i-HiDIC) that does not have both a reboiler and a condenser. To achieve an appropriate heat balance, that is, to operate the column without a reboiler and a condenser, the feed needs to be preheated before entering into the column. In the present work, an i-HiDIC, in which the feed is preheated by distillate vapor (product), was also investigated to enhance the energy saving; this type of i-HiDIC is referred to as i-HIDiC (HX). In addition, to improve the controllability of i-HiDIC, i-HiDIC with a condenser is also investigated; this type of i-HiDIC is referred to as i-HIDiC (L). In most cases, cooling water at normal temperature is used in a condenser. Therefore, the use of a condenser does not deteriorate energy-efficiency of i-HiDIC.

2.2 Dynamic Model

A dynamic simulator was developed by using ASPEN Custom Modeler®. In the simulation model, the mass balance, energy balance, and pressure drop are taken into account. Changes in liquid holdups are calculated by using the Francis weir equation. The other assumptions are as follows:

(1) Tray column is used.
(2) Liquid and vapor on each tray are perfectly mixed and in equilibrium.
(3) Vapor holdup is negligible.
(4) In HIDiC, the rectifying section and the stripping section have the same number of trays and exchange heat between the corresponding trays.
(5) Heat transfer is calculated by $UA\Delta T$ where U is overall heat transfer coefficient, A is heat transfer area, and ΔT is temperature difference between the rectifying section and the stripping section.

2.3 Evaluation of Energy Saving

By using the developed simulator, energy savings of a conventional distillation column (CDiC), HIDiC, and i-HIDiC are investigated under the same separation condition. A standard operating condition is summarized in Table 1. In HIDiC

Table 1. Standard operating condition.

No. of stages	30
Feed stage (top of stripping section)	16
Feed flow rate [kmol/h]	100
Feed temperature [°C]	87
Feed composition Benzene/Toluene	0.5/0.5
Distillate composition (Benzene) [mol%]	99.9
Bottoms composition (Toluene) [mol%]	99.9
ΔP [atm]	1.8
UA [kcal/(h K tray)]	7500

and i-HIDiC, the pressure difference between two sections ΔP is kept at 1.8 atm by a compressor.

The results are shown in Table 2. Heat duty reduction in a condenser does not lead to energy saving directly because the heat can be recovered and inexpensive coolant can be used. Therefore, heat duty in a condenser is not included in the comparison of energy consumption. Energy consumption in HIDiC is 32% less than that in CDiC, and i-HIDiC is more energy-efficient than HIDiC even if the heat duty for preheating feed is considered. Furthermore, energy consumption in i-HIDiC (HX) is 70% less than that in CDiC.

3. CONTROLLABILITY ANALYSIS

Multiloop control systems were designed for various column structures and the control performance was evaluated.

3.1 Control System Design

To evaluate the controllability of various column structures, CDiC and HIDiC were regarded as 2×2 processes. The outputs, i.e., controlled variables, are the mole fraction of benzene in the distillate (x_D) and that of toluene in the bottoms (x_B). On the other hand, the inputs, i.e., manipulated variables, depend on structures. In CDiC, there are three manipulated variables: distillate flow rate (D), reflux flow rate (L), and reboiler heat duty (Q_r). Reflux ratio is investigated later in section 4. In HIDiC, compressor duty (C) is added to these three variables. In i-HIDiC, compressor duty (C) and preheater heat duty (Q_f) are manipulated variables. In i-HIDiC (HX), compressor duty (C) and vapor flow rate supplied to the heat exchanger (V_f) are manipulated variables. In i-HIDiC (L), reflux flow rate (L) is added to these two variables. It was assumed that the pressure at the top of a column and liquid levels of both a reflux drum and a column bottom are perfectly controlled and kept constant at their setpoints.

First, step response tests were conducted and multi-input multi-output (MIMO) transfer function models were identified for each column. The processes were approximated to first-order or second-order lag models. In the step response tests, each manipulated variable was changed in both positive and negative directions to evaluate the degree of nonlinearity that is usually observed when high purity distillation is investigated. To suppress the nonlinearity and derive approximated linear models, the following transformed composition (x^*) was used:

$$x^* = \log \frac{1-x}{1-\tilde{x}} \tag{1}$$

where $\tilde{x}$ is setpoint for x.

In the present work, multiloop control systems were designed for various column structures. Multivariable control was not used here because the objective of the analysis is to investigate the characteristics of various HIDiC structures, not to maximize the control performance. To design multiloop control systems, all possible pairings of controlled and manipulated variables were enumerated, and suitable pairings were selected on the basis of relative gain array (RGA). The relative gain is an index which evaluates process interaction and is calculated from process steady state gains. Here, λ_{ij} is the relative gain which relates the jth manipulated variable and the ith controlled variable. In the case of $\lambda_{ij} \approx 1$, the process interaction is weak and thus it is desirable to choose this pairing. The pairing of $\lambda_{ij} < 0$ should not be selected; rather the pairing of $\lambda_{ij} > 1$ should be selected for 2×2 processes. The selected pairings and the corresponding relative gain values are summarized in Table 3.

After control pairing selection, controllers were designed on the basis of the internal model control (IMC) method. For first-order and second-order lag models, PI and PID controllers are derived, respectively. Both integral time and derivative time are determined automatically from a transfer function model. In this work, a derivative mode filter was used to avoid excessive derivative action. On the other hand, to determine proportional gain, it is necessary to tune the IMC filter time constant τ, which corresponds to the closed-loop time constant. The time constant τ was determined by conducting rigorous dynamic simulations so that ISE becomes as small as possible for both a disturbance and a setpoint change.

3.2 Evaluation Measures

To evaluate the control performance, relative disturbance gain (RDG) and integral error under multiloop control (IEML) are used together with integral squared error (ISE). The controllability

Table 2. Comparison of energy consumption.

	Reboiler	Compressor	Preheater	Total [GJ/h]	HIDiC/CDiC [%]
CDiC	4.49			4.49	100
HIDiC	2.16	0.903		3.06	68
ideal HIDiC		1.35	0.816	2.17	48
ideal HIDiC (HX)		1.35		1.35	30

of a multivariable process is usually dominated by RDG, which is given as the product of relative gain and a disturbance factor. The combined effects of inherent process interaction and disturbance type determine the dominant difference between single-loop and multiloop control performance. RDG becomes small when the control performance is good.

To evaluate the control performance for specific disturbances, IEML can be calculated directly from transfer function models of a process and a disturbance (Stanley et al., 1985). IEML of the controlled variable y_1 is given by

$$\mathrm{IEML}_1 \equiv \left[\int_0^\infty E_1(t)dt\right]_{ML}$$
$$= \left[\int_0^\infty E_1(t)dt\right]_{SL} f_{1,tune}\mathrm{RDG}_1 \quad (2)$$
$$\mathrm{RDG}_1 = \lambda_{11}\left(1 - \frac{K_{d2}K_{12}}{K_{d1}K_{22}}\right) \quad (3)$$

where E_1 denotes an error, K_{di} steady-state gain of a disturbance for the ith controlled variable, respectively. Subscripts SL and ML mean single-loop and multiloop control, respectively. $f_{1,tune}$ is a detuning factor for multiloop control.

3.3 Results and Discussions

To compare the controllability of various column structures, setpoint changes of product compositions and disturbances in feed flow rate and feed composition were investigated. These variables were changed stepwise ±5% from their steady-state values. The results of ISE are summarized in Table 3. Due to space limitation, only ISE results are shown here.

In CDiC, the control performance of the pairing x_D-L and x_B-Q_r is better than the other for the disturbances (a and b), and that of the pairing x_D-D and x_B-Q_r is better for the setpoint changes (c and d). In HIDiC, the control performance of the pairing x_D-L and x_B-Q_r is considerably worse than the others for the disturbance and the setpoint change (a, c, and d). Therefore, it is recommended to use the pairing x_D-D and x_B-Q_r or the pairing x_D-D and x_B-C, the control performance of which is as good as that of CDiC. In addition, the pairing x_D-$Q_r(L)$ and x_B-C can

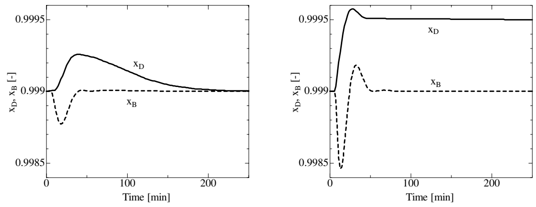


Fig. 2. Control responses of CDiC with (x_D-D, x_B-Q_r) control structure.

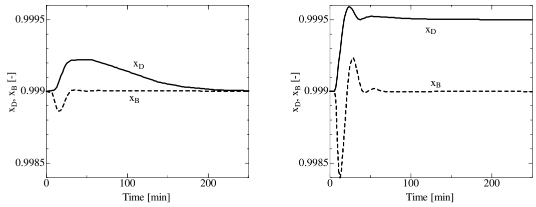


Fig. 3. Control responses of HIDiC with (x_D-D, x_B-Q_r) control structure.

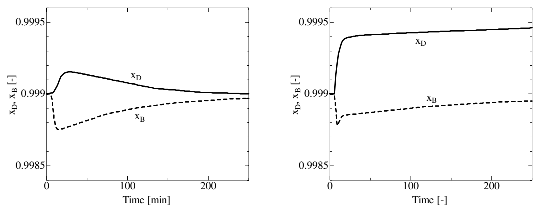


Fig. 4. Control responses of ideal HIDiC (HX) with (x_D-V_f, x_B-C) control structure.

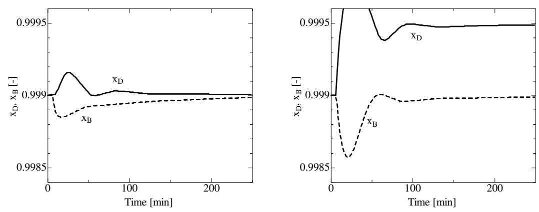


Fig. 5. Control responses of ideal HIDiC (L) with (x_D-L, x_B-C) control structure.

achieve the best control performance of all for the disturbances (a and b); however, this pairing makes the control performance worse for the setpoint changes (c and d). Here, $Q_r(L)$ means the use of Q_r as a manipulated variable under the condition that L is kept constant. Since D cannot be kept constant for satisfying material balance, $Q_r(D)$ cannot be chosen. In i-HIDiC and i-HIDiC (HX), there is only one candidate of pairing. The control performance of both i-HIDiCs is as good as that of CDiC and HIDiC for the disturbances (a and b), but it is worse for the setpoint changes (c and d). In i-HIDiC (L), it is recommended to use the pairing x_D-L and x_B-C or the pairing x_D-D

Table 3. Assessment of control performance. (a: Feed rate change, b: Feed composition change, c: Setpoint change of x_D, d: Setpoint change of x_B)

Type	Sub–Type	Pairing		Relative gain		a	b	c	d
	(A, ΔP)	x_D	x_B	λ					
CDiC		L	Q_r	11.4	ISE	0.00908	0.001	0.011	0.004
		D	Q_r	0.569	ISE	0.018	0.016	0.008	0.003
HIDiC	(12, 1.8)	L	Q_r	245	ISE	0.101	0.011	0.094	0.331
		L	C	11.9	ISE	0.019	0.017	0.018	0.035
		$Q_r(L)$	C	12.5	ISE	0.008	0.006	0.017	0.022
		D	Q_r	0.568	ISE	0.015	0.014	0.008	0.003
		D	C	0.582	ISE	0.015	0.014	0.011	0.004
ideal HIDiC	(12, 1.8)	Q_f	C	8.90	ISE	0.022	0.011	0.012	0.023
ideal HIDiC (HX)	(12, 1.8)	V_f	C	14.2	ISE	0.015	0.017	0.033	0.036
ideal HIDiC (L)	(12, 1.8)	L	C	4.67	ISE	0.004	0.005	0.037	0.013
		D	C	0.582	ISE	0.004	0.005	0.037	0.012
		V_f	C	0.582	ISE	0.014	0.015	0.054	0.032
HIDiC	(12, 1.8)	D	C	0.582	ISE	0.015	0.014	0.011	0.004
	(6, 1.8)	D	C	0.576	ISE	0.021	0.013	0.009	0.003
	(15, 1.8)	D	C	0.582	ISE	0.044	0.042	0.012	0.005
	(12, 1.9)	D	C	0.577	ISE	0.018	0.017	0.015	0.009
	(12, 1.7)	D	C	0.582	ISE	0.015	0.014	0.010	0.004

and x_B-C. As expected, the control performance can be improved by using a condenser.

Control responses for the disturbance in feed flow rate (left) and the setpoint change of the distillate product composition (right) are shown in Figs. 2, 3, 4, and 5. The control responses of CDiC and HIDiC are very similar to each other, and the results reveal that HIDiC can be controlled in the same way as CDiC regardless of the complexity of HIDiC. In addition, control responses of x_D are slower than those of x_B in both CDiC and HIDiC, because the composition in the reboiler is affected immediately by changing Q_r, whereas the composition in the reflux drum is not affected directly by changing D. On the other hand, the control response of i-HIDiC (HX) is different from that of CDiC and HIDiC. It takes a long time in i-HIDiC (HX) for both x_D and x_B to settle at the steady state because i-HIDiC (HX) does not have a reboiler and a condenser. By using a condenser, the control performance of i-HIDiC (L) is improved.

The effects of internal heat transfer area (A) and pressure difference (ΔP) of HIDiC on the control performance were also investigated. The internal heat transfer area of each stage changed from 12 m^2 (benchmark) to 6 and 15 m^2. As a result, the ratio of reboiler heat duty in HIDiC to that in CDiC changed from 50% (benchmark) to 75 and 33%. The pressure difference changed from 1.8 atm (benchmark) to 1.7 and 1.9 atm. The pairing is x_D-D and x_B-C through this investigation. The results show that the control performance of HIDiC becomes worse as the heat transfer area increases. In addition, the control performance of HIDiC becomes slightly worse as the pressure difference increases.

Table 4. Feed and product compositions (wt%) of industrial HIDiC.

	Feed	Distillate	Bottoms
n-butane	0.02	0.16	
i-pentane	1.09	8.77	
n-pentane	11.17	89.76	0.02
2,2-dimethlbutane	0.43	0.02	0.49
cyclopentane	39.00	1.30	44.35
2,3-dimethylbutane	2.19		2.50
2-methylpentane	19.18		21.90
3-methylpentane	7.18		8.20
n-hexane	10.81		12.34
methylcyclopentane	8.71		9.95
cyclohexane	0.22		0.25

Table 5. A standard operating condition of industrial HIDiC.

No. of stages	70
Feed stage (top of stripping section)	36
Feed flow rate [kmol/h]	1286
Feed temperature [°C]	288.1
Distillate composition (2,3-DMB) [wt%]	1.3
Bottoms composition (2,2-DMB+CP) [wt%]	0.509
ΔP [atm]	1.8
UA [kcal/(h K tray)]	1533

Table 6. Energy consumption.

	Total [Mcal/h]	HIDiC/CDiC [%]
simulated CDiC	231	100
simulated HIDiC	174	76
simulated i-HIDiC	142	62
simulated i-HIDiC (HX)	135	58
industrial HIDiC	165	71

4. ANALYSIS OF INDUSTRIAL HIDIC

The feed and standard operating condition of the industrial HIDiC is summarized in Tables 4 and 5. It was confirmed that the developed model can describe the steady state of the industrial HIDiC with sufficient accuracy. The energy-efficiency comparison results are shown in Table 6.

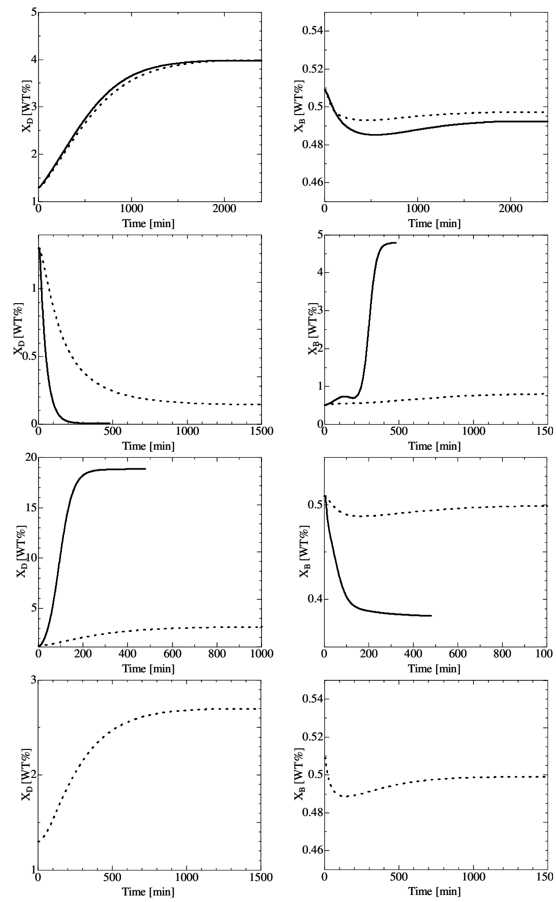


Fig. 6. Simulated step responses of industrial HIDiC and CDiC. (Solid line: CDiC, Dashed line: HIDiC. Step changes in D, L, $Q_r(L)$, and $C(L)$ from the top to the bottom.)

Simulated step responses of the industrial HIDiC are shown in Fig. 6. Although the responses of product compositions in HIDiC from changes in L and $Q_r(L)$ are slower than those in CDiC, the difference between HIDiC and CDiC is small when D is changed. Therefore, control of HIDiC can be easier by using D instead of L as a manipulated variable. In addition, strange responses, which seem to consist of two stages, is observed in x_B when L is changed. Such step responses occurs because physical properties of the key components in the bottoms, i.e., 2,2-dimethlbutane and cyclopentane, are quite different.

By using the developed dynamic simulator, the control performance of various HIDiCs and CDiC is investigated. The control performance of i-HIDiC without a condenser is considerably worse than that of CDiC especially for set-point changes. Therefore, i-HIDiC (L) is strongly recommended. As for control structures, the pairing x_D-V_f and x_B-$C(R)$ is the best of all. Here, R denotes reflux ratio. Although the control performance of i-HIDiC (L) is much better than CDiC for the feed flow rate disturbance, it is worse for the set-point change. To further improve the control performance, decoupling or multivariable control can be used. In the simulation, ISE can be reduced about 40% by using static decouplers.

5. CONCLUSION

In the present work, dynamic models for several types of Heat Integrated Distillation Columns (HIDiCs) were developed, and energy saving, dynamics, and controllability of HIDiC were investigated. In addition, a dynamic model was developed for simulating an existing industrial HIDiC plant to investigate its dynamics and control issues. Although HIDiC has a more complex structure than CDiC, the control performance of HIDiC is comparable to that of CDiC as far as a suitable control system is designed.

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