DETERMINING APPROPRIATE CONFIGURATION OF IDEAL HEAT INTEGRATED DISTILLATION COLUMNS (HIDiC)

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Introduction

The major concern in developing various kinds of heat integrated distillation columns is the strong interaction and high sensitivity resulting from heat integration (Takamatsu, 1996), which could drastically deteriorate system potential performance. Hence, it is of great importance to design processes so as to make these undesired properties as small as possible, namely to increase system dynamic resilience. As for the ideal heat integrated distillation column (HIDiC), we already know that its symmetrical specifications, such as equal feed split, middle feed location and same structures between rectifying and stripping sections, are the main reasons for strong interaction between top and bottom control loops (Huang *et al.*, 1996b). In order to make the ideal HIDiC have higher dynamic resilience, these kinds of symmetrical specifications should be deleted.

In our previous work (Huang *et al.*, 1996c) we already explored how to improve the system resilience through appropriately assigning feed thermal condition q and feed location under general configuration of the ideal HIDiC. As to the effects of symmetrical structure between rectifying and stripping sections, its effects are still not clear. In this work we will concentrate on this problem by studying three possible configurations of the ideal HIDiC. Both time and frequency domain techniques have been employed to assess the potential effects of system configuration towards system performances, and the results obtained are further evaluated through rigorous nonlinear closed-loop simulation.

1. Possible Configurations of the Ideal HIDiC

Figure 1 shows three possible configurations of the ideal HIDiC marked separately as $\Omega 1$, $\Omega 2$ and $\Omega 3$. Configuration $\Omega 2$ is the general structure as studied in our previous work, which possesses the same structures between rectifying and stripping sections and each stage in the rectifying section is connected through a heat exchanger with a corresponding stage

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Table 1 Steady state operating conditions of ideal HIDiC

Configurations		$\Omega 1$	$\Omega 2$	$\Omega 3$
No. of stages	Rectifying section	12	10	10
	Stripping section	10	10	12
Fee stage		13	11	11
Stage holdup		[kmol]	1.0	1.0
Pressure of rectifying section		[MPa]	0.287	0.297
Pressure of stripping section		[MPa]	0.1013	0.1013
Feed flow rate		[kmol/h]	100	100
Feed composition	(Benzene)	0.50	0.50	0.50
	(Toluene)	0.50	0.50	0.50
Feed thermal condition		0.50	0.50	0.50
Relative volatility		2.4	2.4	2.4
Latent heat of vaporization		[kJ/kmol]	30001.1	30001.1
Heat transfer rate		[W/K]	9803	9803
Top product composition		0.995	0.995	0.995
Bottom product composition		0.005	0.005	0.005

Fig. 1 Three possible configurations of ideal HIDiC

in the stripping section; while configurations $\Omega 1$ and $\Omega 3$ are modifications of the configuration $\Omega 2$ where, in addition to the same number of stages coupled through heat exchangers as in configuration $\Omega 2$, two extra stages are added in either the rectifying section (configuration $\Omega 1$) or stripping section (configuration $\Omega 3$). It is considered that by such structural modifications, the symmetrical nature of the configuration $\Omega 2$ would be, to some extent, diminished, and, as a result, the system dynamic resilience could be improved. **Table 1** lists nominal operating conditions for the three systems. Note they are almost the same except for pressure difference, pr-ps, which are slightly different due to the addition of two stages in configurations $\Omega 1$ and $\Omega 3$. Thus, by comparing their steady and dynamic state performances, the effects of system structural modification can be easily detected.

Although the symmetry of configuration $\Omega 2$ can be reduced more significantly by adding more stages in either the rectifying or stripping sections, it may not improve the dynamic performances of the ideal HIDiC much because addition of stages, on the other hand, reduces the pressure difference, pr-ps, between rectifying and stripping sections as well, and hence intensifies the interaction between the two sections. In this work we arbitrarily select two stages just as an illustrative example, while in process design, the

determination of the exact stage number should be based on careful judgment of system performances through rigorous nonlinear simulation.

2. Frequency Analysis of System Performances

The 1, 1 elements (denoted as λ in the following) of relative gain array (RGA) are shown as a function of frequency ω in **Fig. 2**. As can be seen at steady state, the three configurations all have their λ values quite close to 0.5, indicating strong interaction could exist between the top and bottom control loops. With the increasing of frequency ω , the λ value moves away from 0.5 for the configuration $\Omega 1$, indicating the degree of interaction could be, to a certain extent, alleviated, while for the configuration $\Omega 3$, the λ values always stays quite near to 0.5 over almost the entire range of interest, indicating almost no reduction in the degree of interaction between top and bottom control loops. This difference reveals the effects of structural modifications towards the interaction between top and bottom control loops. They could exert influences on it, however, their effects are far different from each other.

With regard to the minimum singular values (MSV) as shown in **Fig. 3**, the configurations $\Omega 1$ and $\Omega 3$ have larger MSV than that of configuration $\Omega 2$, implicating possible performance improvements by modification of the general structure of the ideal HIDiC, *i.e.*, the ability to handle disturbances without saturation of manipulated variables is increased. As far as system sensitivity (**Fig. 4**) is concerned, these structural modifications, however, do not significantly decrease system condition numbers as expected. At low frequency the condition numbers of configuration $\Omega 1$ and $\Omega 3$ are even larger than that of configuration $\Omega 2$. Only beyond some frequencies do they become less than that of configuration $\Omega 2$. This kind of phenomenon demonstrates the complicated

Fig. 2 1,1 RGA element of ideal HIDiC

Fig. 3 Minimum singular values of ideal HIDiC

Fig. 4 Sensitivity indexes of ideal HIDiC

nature of structural modification to system sensitivity. Although it could improve system performances through reducing the degree of interaction between top and bottom control loops and enhancing the ability to handle disturbances, it may also lead to more difficulties in realizing consistent process operation because of resulting stronger gain directionality. Whether or not the system performance could be improved depends upon the net effects of these property changes.

After reexamining Fig. 4 it can be found that configuration Ω1, unlike configuration Ω3, possesses a larger condition number than configuration Ω2 only in a very narrow frequency region, hence it seems to be possible to overcome this drawback through properly designing its control systems. By selecting the bandwidths of control systems beyond the low frequency region, under this circumstance (it should

Table 2 Controller parameters of three configurations Ω1, Ω2 and Ω3

Configurations	Top		Bottom	
	K _c	T _i	K _c	T _i
Ω1	520	0.45	300	0.2
Ω2	400	0.3	300	0.2
Ω3	520	0.45	300	0.2

be located in the region of frequency 1.4~10 rad/h for the configuration Ω1), all its frequency performance indices become better than those of configuration Ω2 and hence could make its performances improved (Morari, 1982; Levien and Morari, 1986; Skogestad, *et al.*, 1990). While for configuration Ω3, because in a large frequency region it possesses largest condition number, we could not expect much improvement in system performance even though careful design of its control systems.

From the above frequency domain analysis, we can also observe that by structural modifications, system high frequency behaviors are improved or at least the same as the original system. This is of special importance for system dynamic resilience because it is directly related to the initial responses of feedback control systems. Based on this point of view, configurations Ω1 and Ω3 are evidently preferred. However, due to the complicated nature of system sensitivity to the system configuration, careful judgment should be made in deciding the best configuration of the ideal HIDiC. It is believed that configuration Ω1 could improve system performance, while configuration Ω3 would not compare with the general configuration Ω2. In other words, structural modifications to the general configuration of ideal HIDiC might not necessarily improve system performances.

3. Nonlinear Closed-loop Simulation and Discussions

3.1 Control system design

The performances of the ideal HIDiC with different configurations are further evaluated through nonlinear dynamic simulation of the process. The dynamic simulation is based on rigorous tray-to-tray calculation of material and energy balance equations in conjunction with vapor-liquid equilibrium (Huang *et al.*, 1996a), and control system (Table 2) are designed through an experimental approach in a consistent manner (Finco and Luyben, 1987; Huang *et al.*, 1996c). Note in Fig. 2, the λ values for configurations Ω1 and Ω3 are less than 0.5 at relative higher frequency. The appropriate control structure for them should thus be y_1 - q , x_{20} - pr . In order to

Table 3 Integral square errors of control systems

Configurations	$\Omega 1$	$\Omega 2$	$\Omega 3$
Servo control			
Top	7.05207×10^{-8}	8.93069×10^{-8}	8.01647×10^{-8}
Bottom	1.95606×10^{-8}	2.05201×10^{-8}	2.53759×10^{-8}
Regulatory control			
Top	1.38522×10^{-7}	1.56002×10^{-7}	1.84325×10^{-7}
Bottom	3.90438×10^{-9}	6.53794×10^{-9}	5.18228×10^{-8}

Fig. 5 Transient responses of product composition after setpoint of top control loop is disturbed from 0.995 to 0.994 **Fig. 6** Transient responses of product composition after feed composition is increased 5% from its steady state value

easily compare system performances, the same control structure is also adopted for configuration $\Omega 2$.

3.2 Servo control

Because of the dominating effects of feed thermal condition q on the interaction between top and bottom control loops, the top control system is selected to perform the servo simulation experiments. **Fig. 5** shows the servo responses of the ideal HiDiC under different configuration when the setpoint of the top control system is changed -0.01 from its original value 0.995. The corresponding date of integral square error (ISE) of the control systems are tabulated in **Table 3**. As predicted in the frequency domain analysis, the configuration $\Omega 1$ outperforms the

configurations $\Omega 2$ and $\Omega 3$ in setpoint transitions, and configuration $\Omega 3$ gives the worst response with largest oscillation. The same tendency of system performances can also be observed from **Table 3**.

3.3 Regulatory control

As discussed in our previous work, the effects of feed composition disturbances are much severer than that of feed flow rate disturbances, hence to examine the ability of control systems to reject feed composition disturbances is of top priority. **Fig. 6** compares regulation responses of control systems of the ideal HiDiC under different configurations when feed composition is subjected to 5% changes, and the corresponding ISE date are also shown in **Table 3**.

Again in this situation the configuration $\Omega 1$ produces the best responses and configuration $\Omega 3$ gives the worst ones. These results further justify the conclusions we obtain from frequency domain analysis.

3.4 Discussions

The initial responses of control systems have been improved by the structural modifications where the first and second overshoots have been reduced, especially in the case of regulatory control. When approaching the steady states the response of configuration $\Omega 3$ appears quite oscillatory. This sharp difference in system responses between configurations $\Omega 1$ and $\Omega 3$ reveals clearly the strong effects of high condition number. Although the same number of stages are added to the general configuration of the ideal HIDIc in configurations $\Omega 1$ and $\Omega 3$, their effects appear quite different. In order to design the ideal HIDIc correctly and efficiently determination of configuration based on not only frequency domain analysis but time domain comparisons as well is suggested.

Although the ideal HIDIc's performances can be improved by structural modification shown in the case of configuration $\Omega 1$, the effects of these structural changes appear not to be as strong as expected. This is mainly due to neglecting of stage hydraulics (no liquid hydraulic lag) in the modeling of the process, which still causes the ideal HIDIc to possess strong symmetry even though structural modification has been made, for instance, the addition of stages does not have any effect upon internal flow rates and the vapor flow rate in the stripping section is always equal to the corresponding liquid flow rate in the rectifying section. Therefore, it is believed that the results obtained in this work are much more conservative than reality.

Conclusion

The symmetrical structure between rectifying and stripping sections of the ideal HIDIc contributes substantially to the interaction between top and bottom control loops. By adding some stages to either the rectifying section or the stripping section, the degree of symmetry can be, to a certain degree, alleviated and the system high frequency behavior which is of primary importance for feedback control, can be improved. However, several points should be remembered.

- 1) Structural modifications may reduce the degree of interaction between top and bottom control loops. However, sometimes it may fail.
- 2) The system ability to reject disturbances appears to be improved with structural modifications to the general ideal HIDIc.

3) Structural modifications appear to be able to decrease system gain directionality at high frequencies, while it may also increase the system inadequacy at low frequencies.

Owing to these reasons, the determination of detailed configurations of the ideal HIDIc should be based on careful judgment of system performances through both time and frequency domain analysis.

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Nomenclature

Kc	=	proportional gain of controllers	[—]
pr	=	pressure of rectifying section	[kPa]
ps	=	pressure of stripping section	[kPa]
q	=	thermal condition of feed	[—]
T _i	=	integral time constant of controllers	[s]
x	=	mole fraction of liquid	[—]
y	=	mole fraction of vapor	[—]
γ	=	condition number	[—]
σ	=	singular value	[—]
λ	=	1,1 element of RGA	[—]
ω	=	frequency	[s ⁻¹]
$\Omega 1, \Omega 2, \Omega 3$	=	process configuration	[—]
ISE	=	integral square error	[—]
MSV	=	minimum singular value	[—]
RGA	=	relative gain array	[—]

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