## RESEARCH PAPERS

# Dynamics and control designs for internal thermally coupled distillation columns with different purities, Part 1: Open loop dynamic behaviors*

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**Abstract** The open loop dynamic behaviors of internal thermally coupled distillation column with four different purities (low-, moderate-, high- and very high-purity) are studied. These dynamic behaviors are characterized by strong asymmetric non-linearity, high sensitivity to operation conditions change and distinct inverse response. With the increase of purity, these dynamic behaviors are intensified and become more complex, which easily lead to the mismatch between linear model and plant and also change the relationship between manipulated and controlled variables.

**Keywords:** **thermal coupling, inverse response, non-linearity, high purity, asymmetric behavior.**

Distillation is the most widely used separation operation in the chemical process industries and it consumes a large amount of energy. According to some recent estimates, about 40% of energy involved in refining and other continuous chemical process in USA is consumed in distillation and this represents nearly 4% of the total energy consumption in USA in 1988[1]. To improve the energy efficiency of distillation, various distillation methods have been proposed[2], such as heat pump columns, multi-effect columns, Petlyuk columns and secondary reflux and vaporization (SRV). Except for SRV method, the former three distillation methods have already been industrialized in practical chemical process[3,4].

Internal thermally coupled distillation column (ITCDIC) employs SRV method and introduces internal heat integration between the rectifying and the stripping sections into the distillation system. This novel distillation column has received increasing attention in recent years due to its great energy efficiency and its low expenditure of external operation facilities (Fig. 1)[1,2,5–7]. ITCDIC, without conventional condenser and conventional re-boiler, generally offers higher energy efficiency than conventional distillation columns as well as other types of energy-saving distillation columns, such as heat pump columns and Petlyuk columns according to rigor thermodynamic analysis[2].

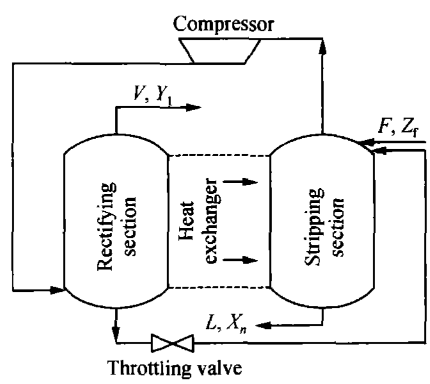


Fig. 1. Schematic diagram of ITCDIC ($Y_1$ is overhead product purity, $X_n$ is bottom product purity, $V$ is vapor flow rate, $L$ is liquid flow rate, $F$ is feed flow rate and $Z_f$ is feed composition).

Although internal heat integration of SRV method has great potential of energy saving, it also leads to complex dynamic behavior, which poses a great challenge for control design. Very few papers consider the dynamics and control of different purities and operation conditions of ITCDIC. Pervious research work about ITCDIC focused mainly on moder-

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ate-purity system. Huang[7] proposed internal model control (IMC) and Liu[6] presented decentralized PID control for the moderate system. However, both schemes are unable to provide satisfactory control performance for high- and very high-purity systems. Despite a large economic incentive from high- and very high-purity products[8—10], highly complex and distinct dynamic behavior makes designing effective control schemes more difficult for high- and very high-purity ITCDIC, which considerably limits the practical application of ITCDIC in the chemical process.

This study first investigates the complex open loop dynamic behavior of ITCDIC with four different purities including low-, moderate-, high- and very high-purities. To obtain some insight into the dynamic difficulties associated with designing appropriate control schemes for different purities, some distinct dynamic behavior leading to severe mismatch between linear model and plant is further studied. In addition, the effects of increased purity on dynamic behavior and heat integration are described and analyzed in detail.

## 1 Systems studied

Four distillation columns with different product purities and different operation conditions are studied. Besides, a binary mixture, benzene-toluene, is exploited as an illustrative example. The detailed operating conditions are shown in Table 1. The following simulations are based on the dynamic model proposed by Liu in 2000[6], consisting of energy balances, material balances and vapor-liquid equilibrium. In addition, the pressure difference between the rectifying and the stripping sections, $P_r$-$P_s$, and feed thermal condition, $q$, are selected as manipulated variables to control the overhead and bottom product compositions.

Table 1. Operating conditions used for the simulations

| Purity | Low | Moderate | High | Very high |
|---|---|---|---|---|
| Distillation product specification | 0.9500 | 0.9800 | 0.9990 | 0.9999 |
| Bottom product specification | 0.0500 | 0.0400 | 0.0030 | 0.0001 |
| Stage number | 24.0000 | 30.0000 | 40.0000 | 58.0000 |
| Feed stage | 13.0000 | 16.0000 | 21.0000 | 30.0000 |
| Feed flow rate [kmol/h] | 100.0000 | 100.0000 | 100.0000 | 100.0000 |
| Feed composition, (Benzene) | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| (Toluene) | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| Feed thermal condition | 0.5000 | 0.5107 | 0.5010 | 0.5000 |
| Pressure of rectifying section [MPa] | 0.3195 | 0.3006 | 0.3387 | 0.3064 |
| Pressure of stripping section [MPa] | 0.1013 | 0.1013 | 0.1013 | 0.1013 |
| Heat transfer rate [W/k] | 9803.0000 | 9803.0000 | 9803.0000 | 9803.0000 |
| Latent heat of vaporization [kj/kmol] | 30001.1000 | 30001.1000 | 30001.1000 | 30001.1000 |
| Relative volatility | 2.3170 | 2.3170 | 2.3170 | 2.3170 |
| Liquid holdup [kmol] | 1.5000 | 1.5000 | 1.5000 | 1.5000 |

## 2 Open-loop dynamic behavior

### 2.1 Plant non-linearity

Fig. 2 shows the responses to ± 1% step changes from the initial value of pressure difference, $P_r$-$P_s$, between the rectifying and the stripping sections. The responses to ± 1% changes in feed thermal condition $q$ are given in Fig. 3. It shows that $q$ has a stronger effect on both end product compositions than $P_r$-$P_s$.

In addition, the degree of non-linearity in responses to both $P_r$-$P_s$ and $q$ increases with the increasing purity. In low-purity system, positive and negative perturbation leads to a little bit different response. Its non-linearity exists but is not very high, so linear model is capable of describing the real plant accurately. However, in moderate-purity system, the responses to positive and negative changes are completely different in terms of time constant and deviation. Therefore, mismatch between linear model and real plant exists and this mismatch can limit control performance of some model-based control schemes[11]. In the high- and very high-purity system, non-linearity is further intensified with the increasing purity. Positive perturbation of feed thermal condition results in the relatively large deviation, sluggish response of bottom product composition, little deviation, and quick response of overhead product composition. On the contrary, negative perturbation has opposite effects on both of the two end compositions.

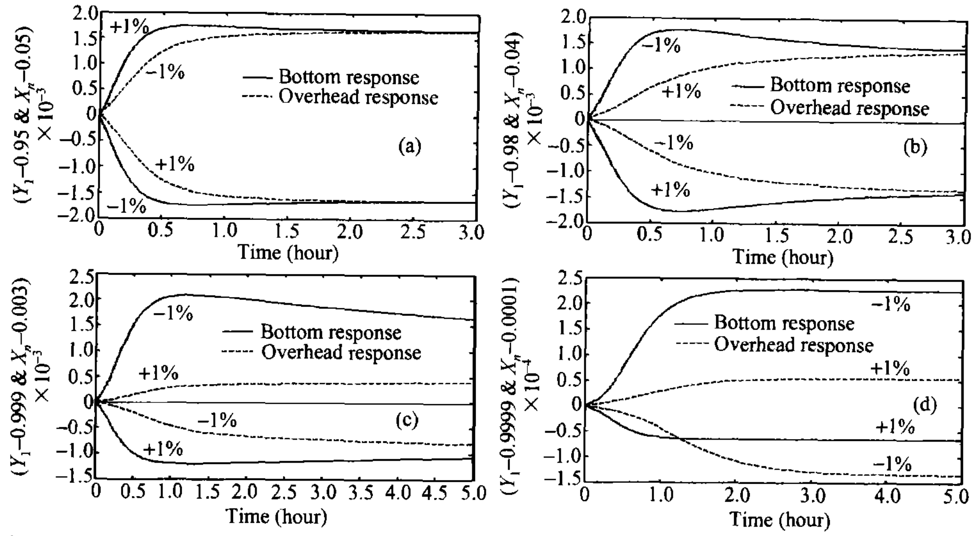


Fig. 2. The responses to ±1% step changes of $P_r$-$P_s$. (a) Low-purity; (b) moderate-purity; (c) high-purity; (d) very high-purity.

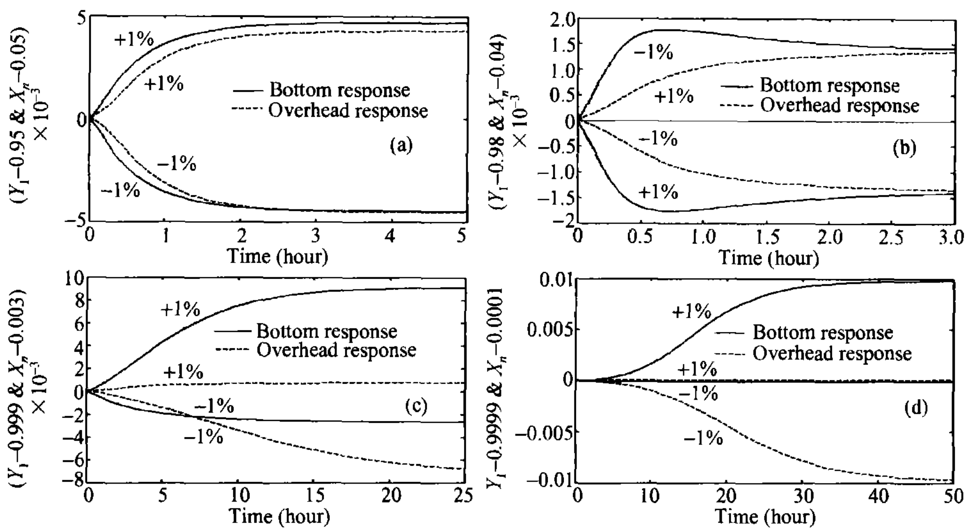


Fig. 3. The responses to ± 1% step changes of $q$. (a) Low-purity; (b) moderate-purity; (c) high-purity; (d) very high-purity.

In addition to different time constants and deviations, non-linearity also considerably changes the way in which the manipulated variables $P_r$-$P_s$ and $q$ affect the controlled variables. Figs. 4 and 5 show responses of the bottom product compositions to feed thermal condition $q$ leaving from its initial value by +5% at the beginning and then back to its initial value. It is observed that the leaving and back transients between two steady-state values have completely different lastings in the high- and very high-purity systems. This phenomenon is called asymmetric dynamics, which is a severe and distinct non-linearity[12,13]. $P = T_2/T_1$ can be used to describe the difference of leaving and back time. The larger the value $P$ is, the stronger the asymmetric behavior is. The degree of asymmetric behavior increases with increasing purity (Table 2). Asymmetric behavior on overhead end is stronger than that on the bottom end. Furthermore, asymmetric dynamics in the low- and moderate-purity system is not obvious. Due to strong asymmetric dynamic behavior in high- and very high-purity systems, linear analysis of relationship between manipulated variables ($P_r$-$P_s$ and $q$) and product compositions is not accurate for tight control of high- and very high-purity systems.

Table 2. Asymmetric behavior of different purities

| Value $P$ | Overhead | Bottom |
|---|---|---|
| Low-purity | 1.639 | 1.573 |
| Moderate-purity | 1.942 | 1.736 |
| High-purity | 3.867 | 3.203 |
| Very high-purity | 7.321 | 6.714 |

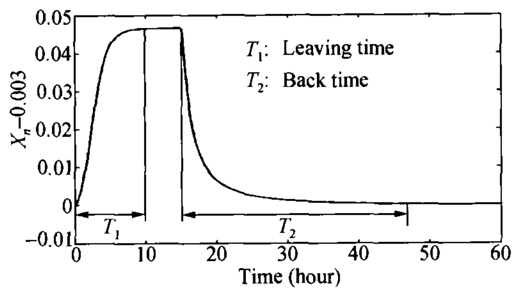


Fig. 4. The asymmetric responses to $q$ in high-purity.

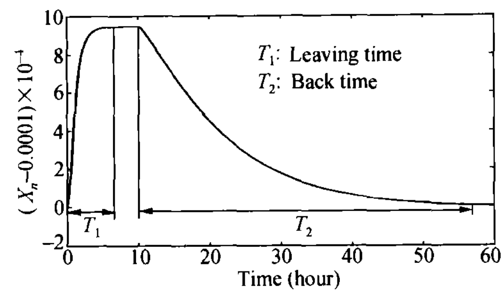


Fig. 5. The asymmetric responses to $q$ in very high-purity.

2.2 Sensitivity to operation condition changes

Fig. 6 shows the transient responses of two end products in four different purity systems after the feed composition, $Z_f$, is disturbed $\pm 15\%$ from its steady state values. We can see that the non-linearity of responses to feed composition is strongly intensified as purity increases. Increased non-linearity in high- and very high-purity system leads to different sensitivities of two end products to $Z_f$. In these systems, the bottom product composition is extremely sensitive to the positive disturbance of $Z_f$ and less sensitive to the negative disturbance of $Z_f$. On the other hand, the situation is opposite to the overhead product composition. Besides, the higher the purity is, the more sluggish the response is. Hence, during the design of control systems, special attention should be paid to the rejection of feed composition disturbances that have great influence on both overhead and bottom products among all four different purity systems.

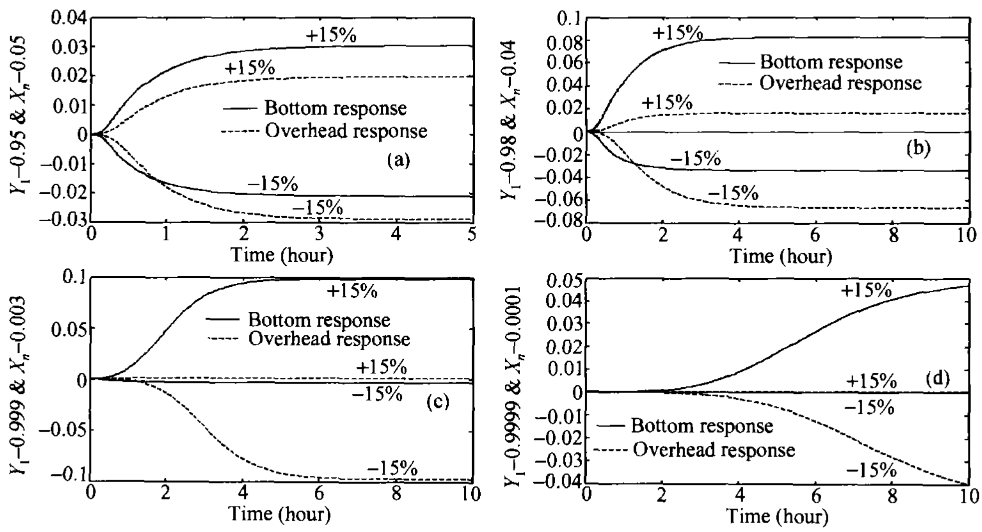


Fig. 6. The responses to $\pm 15\%$ step changes of $Z_f$. (a) Low-purity; (b) moderate-purity; (c) high-purity; (d) very high-purity.

Fig. 7 shows the overhead and bottom responses to $\pm$ 15% disturbance of feed flow rate, $F$, from steady state values. The degrees of non-linearity are not obvious in low- and moderate-purity systems, while severe non-linearity and extremely sluggish responses of high- and very high-purity systems are observed. As a result, both product compositions will be less influenced than feed composition in low- and moderate-purity systems.

However, intensified non-linearity and sluggish responses in the high- and very high-purity system indicate that rejection of feed flow rate should be taken into account when designing tight control schemes.

The responses to $Z_f$ and $F$ give us the insight that high- and very high-purity ITCDIC is more sensitive to external disturbances of operation conditions than low- and moderate-purity systems. The degree of sensitivity to operation conditions is reinforced by internal heat integration. In ITCDIC system, heat integration transfers the effect of any external disturbance of operation condition from one column to another column, so that external disturbances affect the rectifying and the stripping sections simultaneously and immediately. Moreover, the total heat integration of ITCDIC increases with increasing purity, which can be observed in Fig. 8. As a result, with the help of heat integration, the external disturbances of operation condition have intensified influence on overall distillation columns.

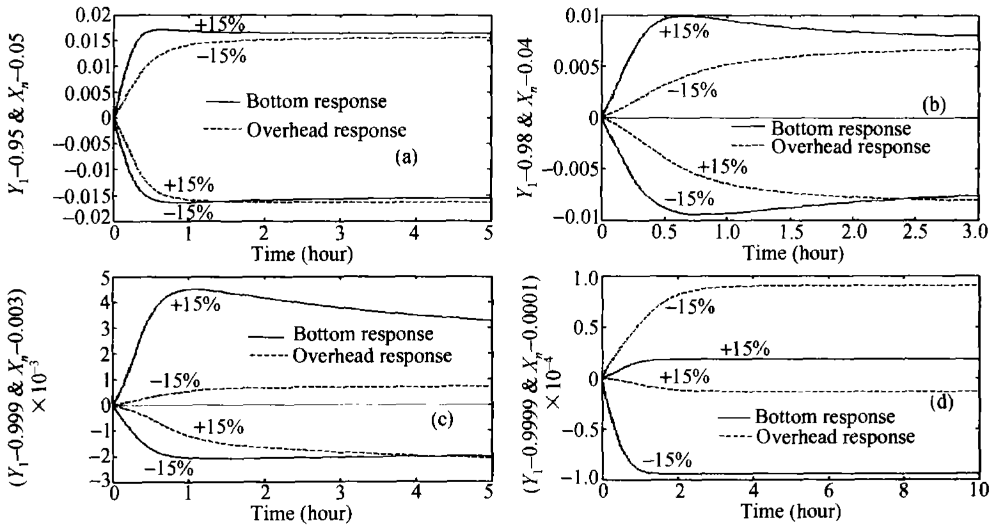


Fig. 7. The responses to ±15% step changes of $F$. (a) Low-purity; (b) moderate-purity; (c) high-purity; (d) very high-purity.

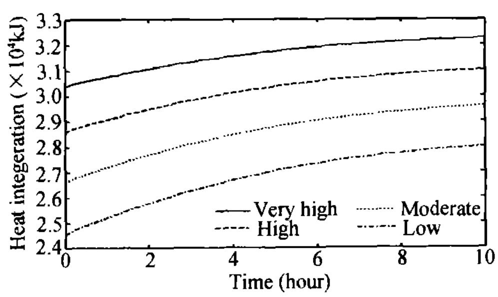


Fig. 8. Heat integration change when the feed thermal condition $q$ increases +3% in four different purity ITCDIC systems.

Therefore, the heat integration between rectifying and stripping sections gives the ITCDIC a special feature of high sensitivity to operation conditions, which means that the overhead and bottom product compositions are easily affected by operation condition changes.

## 2.3 Two effects of inverse response

Another distinct feature in ITCDIC system is inverse response, which is firstly found in this work. Inverse response means that the initial responses of the output variables are in the opposite direction where they eventually end up[14]. Fig. 9 shows the open-loop response of overhead and bottom product compositions for a 0.5% positive step change of feed thermal condition, $q$. Inverse responses are not obvious in low- and moderate-purity systems. Inverse time of very high-purity system is the longest among four different systems, since the degree of inverse responses is reinforced when the purity increases. Table 3 gives the inverse time of high- and very high-purity ITCDIC systems. It shows that inverse response on overhead end is stronger than that on bottom end.

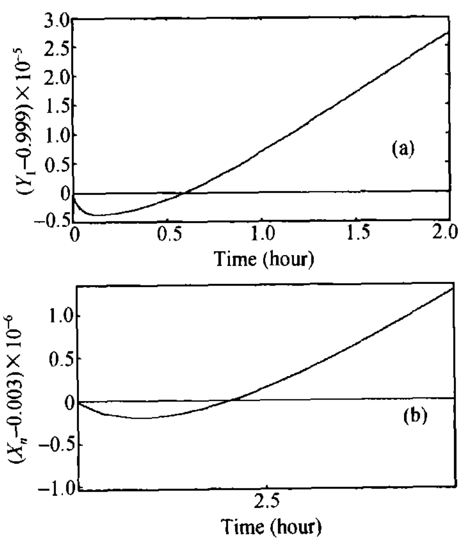


Fig. 9. Inverse response of overhead and bottom product in high-purity system: (a) Overhead; (b) bottom.

Table 3. Inverse time of two different purities

| Inverse time | Overhead (min) | Bottom (min) |
|---|---|---|
| High-purity | 34 | 2 |
| Very high-purity | 48 | 6 |

To analyze the inverse responses, internal heat integration and vapor flow rate should be taken into account. The product composition is considerably influenced by $V$, since vapor flow rate can drive light material to the overhead end of columns. On one hand, increase of $q$ tends to decrease the vapor flow rate by reducing parts of the feed flow rate, $F(1-q)$, which is added into $V$. Hence, $q$ affects $V$ in a negative direction. When $q$ increases, it momentarily reduces $V$. On the other hand, in ITCDIC, vapor boil-up $V$ is also affected by the total value of heat integration, since the heat transfer from each tray of rectifying section to that of stripping section directly provides the vapor flows for ITCDIC system in which neither re-boiler nor condenser presents. The heat integration value increases with the increasing $q$. As a result, $q$ has a positive influence on $V$ and increase of $q$ can lead to the momentary increase of $V$ through heat integration.

Due to these two opposite effects, inverse response of product composition takes place and becomes more severe when purity increases. Stephanopoulos classified the inverse response into non-minimum phase response[15]. Inverse response poses a great challenge to control schemes and degrades control performance, since controller has to wait for the inverse response to elapse before a true reaction appears. Shinskey pointed out that inverse response delays the control loop in much the same way as the dead time[16]. Therefore, the feed thermal condition, $q$, provides a poor feedback control to overhead product, and suitable compensator should be designed and added into systems to overcome these two opposite effects of inverse response.

## 4 Conclusions

This work has shown that ITCDIC possesses some distinct dynamic behaviors, which should be taken into account in designing control schemes: (1) Strong asymmetric nonlinearity causes great difference of the leaving and back setting times of manipulated variables so that linear model can not well describe this nonlinear system. (2) The sensitivity to the change of operation conditions is intensified by internal heat integration. Any external disturbance affects the rectifying and the stripping sections simultaneously since heat integration can transfer disturbance from one column to another. (3) Inverse response delays the dynamic response as the dead time does and introduces non-minimum phase into system. Furthermore, these three kinds of distinct and complex behavior are intensified when purity increases, which yields mismatches between linear model and plant.

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