Control Structures for Disturbance Rejection and Decoupling of Distillation

The process gains for different distillation control structures can be calculated through transformations from known gains of one arbitrary structure.

In this paper the transformation is utilized for calculation of a two-point distillation control structure which, in the steady state, simultaneously rejects disturbances in the feed composition and in the feed flow rate and results in implicit decoupling between the two product control loops. This disturbance rejecting and decoupling (DRD) structure is tested on a model of a 15-plate pilot-plant distillation column. It compares favorably with standard structures for dual composition control. Experimental results agree with the simulation results.

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Introduction

Multivariable control systems are often decomposed into multiloop single-input single-output (SISO) systems, often for good reasons. SISO systems are much easier to design and operate than multiinput multioutput (MIMO) systems. Also, the various control loops of a process often work in different time scales, which makes decomposition natural.

When a MIMO control problem is decomposed into several SISO loops, the way the decomposition is made can be very important. In the case of a continuous binary distillation column where the aim is to control both products, the pressure control being neglected, four flows are usually used as manipulators: the reflux flow L, the boilup V (normally manipulated through heat input to the reboiler), and the two product flows D and B. There are four variables to be controlled: two product properties (composition or temperature), the reflux drum level, and the reboiler level.

If a true multivariable theory, such as linear-quadratic (LQ) control, is used to design the control system, the result is that all four outputs should be connected to all four manipulators. In industrial practice, however, the control task is almost always divided into two subsets: inventory control and product control. In fact, the discussed control problem is usually further decomposed into four SISO loops.

This decomposition into four SISO loops can be made in many ways. Two common control structures are the (L, V) and (D, V) structures. In the (L, V) structure, Figure 1, L and V are used for control of the products, whereas D and V are used for the same purpose in the (D, V) structure, Figure 2. (In Figures 1 and 2 the product properties are inferred from temperature measurements in the column.) However, when one considers that not only pure flows like L and D can be used as control variables, but also various functions of L and D, such as $D/(L + D)$, it is easy to see that the control can be accomplished through an infinite number of multiloop SISO structures.

Do these different structures have different properties in any important way? The answer is affirmative. One important aspect is illustrated in Figure 3, where the "open-loop" responses to a step disturbance in the feed composition are shown for four structures. "Open-loop" is defined here as the open composition (temperature) control loops with only the two inventory control loops closed. Figure 3 shows that various structures may reject disturbances very differently; they may be self-controlling to very different degrees. This important point has also been discussed by Shinskey (1985).

There are also other important differences between the structures. The interaction between the control loops is normally different, and the nonlinearities of the system can have varied effects depending on the structure. Also, the robustness of structures can differ considerably (Skogestad et al., 1988).

Since structures and processes can have considerably diverse properties, several structures may have to be investigated to find a good control structure for a process. It would be highly desirable to have methods by which arbitrary structures could be investigated from known properties of one structure. One would not then have to experimentally determine more than one structure.

Transformations of the process model expressing the relation between the manipulators and the outputs have previously been

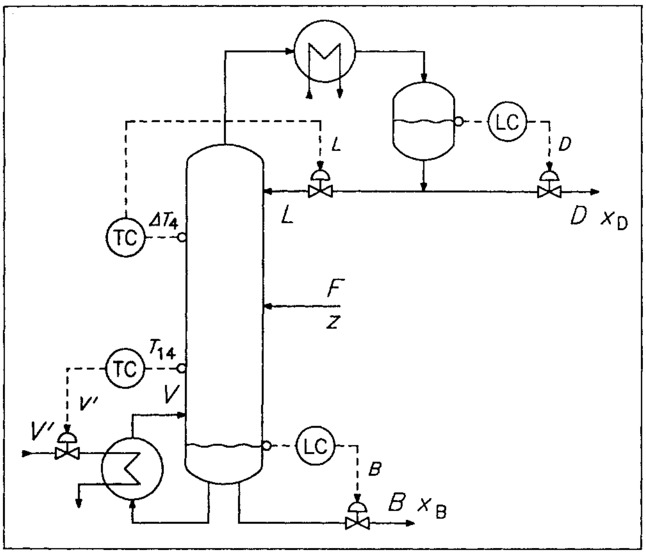

Figure 1. Implementation of the (*L*, *V*) control strategy.

treated by Häggblom and Waller (1988). In this paper the treatment is generalized to include disturbances affecting the process. The transformations are then utilized to synthesize a control structure resulting in perfect steady-state disturbance rejection and decoupling.

Transformations between Control Structures

The transformations are illustrated by means of the process gains, that is, the steady-state part of the transfer functions. The same transformations, however, are valid for the complete transfer functions if the column inventory is perfectly controlled or if the inventory control manipulators are not changed through the transformation. In distillation, perfect inventory control is often a good approximation since the inventory control loops usually are much faster than the composition control loops.

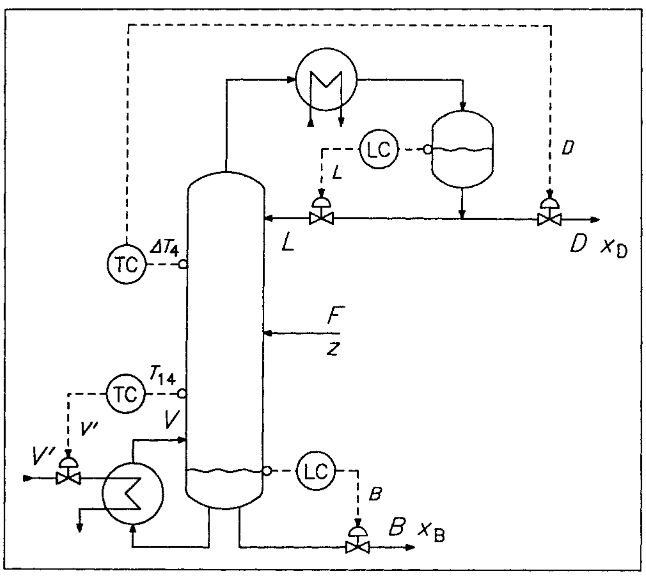

Figure 2. Implementation of the (*D*, *V*) control strategy.

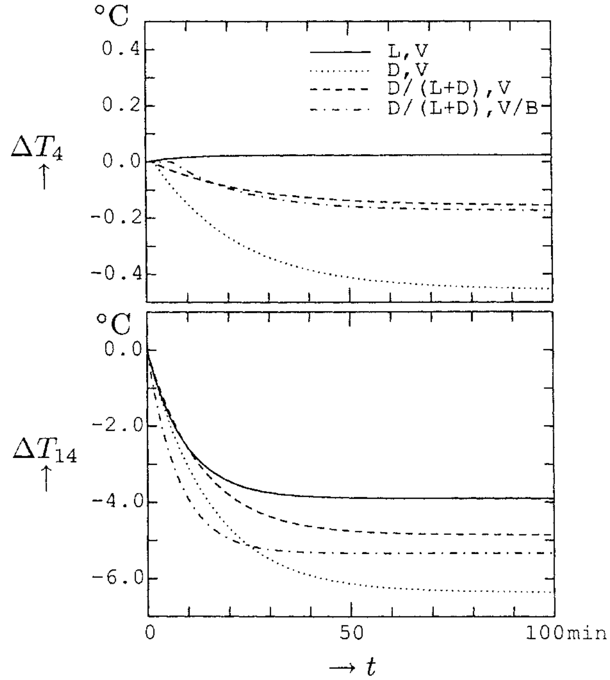

Figure 3. "Open-loop" responses to a step disturbance of 6 wt.% in the feed composition for four control structures.

Dynamic transformations are illustrated quantitatively by Häggblom and Waller (1988).

Assume that the two product properties y and x (compositions or temperatures) are controlled by L and V and the column inventory by D and B, where V also can denote the heat input to the reboiler. The feed flow rate F and the feed composition z are disturbance variables. A steady-state model for the process is then

$$\begin{bmatrix} \Delta y \\ \Delta x \end{bmatrix} = \begin{bmatrix} K_{yL}^{LV} & K_{yV}^{LV} \\ K_{xL}^{LV} & K_{xV}^{LV} \end{bmatrix} \begin{bmatrix} \Delta L \\ \Delta V \end{bmatrix} + \begin{bmatrix} K_{yF}^{LV} & K_{yz}^{LV} \\ K_{xF}^{LV} & K_{xz}^{LV} \end{bmatrix} \begin{bmatrix} \Delta F \\ \Delta z \end{bmatrix} \tag{1a}$$

$$\begin{bmatrix} \Delta D \\ \Delta B \end{bmatrix} = \begin{bmatrix} K_{DL}^{LV} & K_{DV}^{LV} \\ K_{BL}^{LV} & K_{BV}^{LV} \end{bmatrix} \begin{bmatrix} \Delta L \\ \Delta V \end{bmatrix} + \begin{bmatrix} K_{DF}^{LV} & K_{Dz}^{LV} \\ K_{BF}^{LV} & K_{Bz}^{LV} \end{bmatrix} \begin{bmatrix} \Delta F \\ \Delta z \end{bmatrix} \tag{1b}$$

Published data on process models for the distillation process usually include only the part corresponding to Eq. 1a, not the one corresponding to Eq. 1b. However, Eq. 1b is needed also if the model is to be transformed to other structures. If the primary output variables are product compositions, the gains in Eq. 1b can, in fact, be calculated from the gains in Eq. 1a and some steady-state data, but not if they are other kinds of variables such as temperatures (Häggblom and Waller, 1988).

The complete model (Eq. 1) for the (*L*, *V*) structure can be transformed to models for other structures. Consider, for instance, a model for the (*D*, *V*) structure

$$\begin{bmatrix} \Delta y \\ \Delta x \end{bmatrix} = \begin{bmatrix} K_{yD}^{DV} & K_{yV}^{DV} \\ K_{xD}^{DV} & K_{xV}^{DV} \end{bmatrix} \begin{bmatrix} \Delta D \\ \Delta V \end{bmatrix} + \begin{bmatrix} K_{yF}^{DV} & 5_{yz}^{DV} \\ K_{xF}^{DV} & K_{xz}^{DV} \end{bmatrix} \begin{bmatrix} \Delta F \\ \Delta z \end{bmatrix} \tag{2}$$

where, for the sake of brevity, only the part comprising the primary outputs is given.

The gains in Eq. 2 are obtained from Eqs. 1 as follows. Equation 1b gives:

$$\Delta L = \frac{1}{K_{DL}^{LV}}\Delta D - \frac{K_{DV}^{LV}}{K_{DL}^{LV}}\Delta V - \frac{K_{DF}^{LV}}{K_{DL}^{LV}}\Delta F - \frac{K_{Dz}^{LV}}{K_{DL}^{LV}}\Delta z \tag{3}$$

which can be used to eliminate ΔL from Eq. 1a. The result is that the matrices in Eq. 2 are given by

$$\begin{bmatrix} K_{yD}^{DV} & K_{yV}^{DV} \\ K_{xD}^{DV} & K_{xV}^{DV} \end{bmatrix} = \begin{bmatrix} \frac{K_{yL}^{LV}}{K_{DL}^{LV}} & K_{yV}^{LV} - K_{yL}^{LV}\frac{K_{DV}^{LV}}{K_{DL}^{LV}} \\ \frac{K_{xL}^{LV}}{K_{DL}^{LV}} & K_{xV}^{LV} - K_{xL}^{LV}\frac{K_{DV}^{LV}}{K_{DL}^{LV}} \end{bmatrix} \tag{4a}$$

and

$$\begin{bmatrix} K_{yF}^{DV} & K_{yz}^{DV} \\ K_{xF}^{DV} & K_{xz}^{DV} \end{bmatrix} = \begin{bmatrix} K_{yF}^{LV} - K_{yL}^{LV}\frac{K_{DF}^{LV}}{K_{DL}^{LV}} & K_{yz}^{LV} - K_{yL}^{LV}\frac{K_{Dz}^{LV}}{K_{DL}^{LV}} \\ K_{xF}^{LV} - K_{xL}^{LV}\frac{K_{DF}^{LV}}{K_{DL}^{LV}} & K_{xz}^{LV} - K_{xL}^{LV}\frac{K_{Dz}^{LV}}{K_{DL}^{LV}} \end{bmatrix} \tag{4b}$$

The part of the (D, V) model accounting for inventory control has ΔL and ΔB as outputs. ΔL is given by Eq. 3 and the expression for ΔB is obtained by elimination of ΔL from Eq. 1b using Eq. 3.

As shown by this example, a number of process gains need to be known in order to make the transformation. However, several of these gains are related through constraints on the process. In this case, $F = D + B$ in the steady state is such a constraint. This means that the model in Eq. 1 contains redundant information, which means that several of the gains in Eq. 1 can be calculated from other gains in Eq. 1 through consistency relations. Such consistency relations are described by Häggblom and Waller (1988).

Some consistency relations needed in the sequence are derived as follows. Continuous operation of the process requires that the overall material balances are satisfied at steady state. Then

$$F = D + B \tag{5a}$$

Linearization of Eq. 5a around a steady state gives

$$\Delta F = \Delta D + \Delta B \tag{5b}$$

The inputs of the model in Eq. 1 are independent variables. Therefore, a change in L, for example, causes changes in D and B such that $\Delta D = K_{DL}^{LV}\,\Delta L$ and $\Delta B = K_{BL}^{LV}\,\Delta L$. Since F is not affected by L, Eq. 5b gives $K_{DL}^{LV} + K_{BL}^{LV} = 0$. In a similar way, the following consistency relations between the process gains in Eq. 1 are obtained by means of Eq. 5b:

$$K_{DL}^{LV} + K_{BL}^{LV} = 0 \tag{6a}$$

$$K_{DV}^{LV} + K_{BV}^{LV} = 0 \tag{6b}$$

$$K_{DF}^{LV} + K_{BF}^{LV} = 1 \tag{6c}$$

$$K_{Dz}^{LV} + K_{Bz}^{LV} = 0 \tag{6d}$$

In order to derive a general formula for transformation between structures, consider Eq. 1, which can be written compactly as

$$\begin{bmatrix} \Delta \boldsymbol{y} \\ \Delta \boldsymbol{v} \end{bmatrix} = \begin{bmatrix} \boldsymbol{K}_{yu} \\ \boldsymbol{K}_{vu} \end{bmatrix} \Delta \boldsymbol{u} + \begin{bmatrix} \boldsymbol{K}_{yw} \\ \boldsymbol{K}_{vw} \end{bmatrix} \Delta \boldsymbol{w} \tag{7}$$

where

$\boldsymbol{y} = [y\,x]^T$, $\boldsymbol{v} = [D\,B]^T$, $\boldsymbol{u} = [L\,V]^T$, and $\boldsymbol{w} = [F\,z]^T$.

A model for an alternative control structure has another set of input variables $\boldsymbol{\mu}$ (corresponding to $\boldsymbol{u}$) and dependent manipulators $\boldsymbol{\nu}$ (corresponding to $\boldsymbol{v}$). Denote the disturbances corresponding to $\boldsymbol{w}$ by $\boldsymbol{\omega}$ in the alternative control structure.

Next, consider a linear variable transformation

$$\begin{bmatrix} \Delta \boldsymbol{\nu} \\ \Delta \boldsymbol{\mu} \\ \Delta \boldsymbol{\omega} \end{bmatrix} = \begin{bmatrix} \boldsymbol{H}_{\nu v} & \boldsymbol{H}_{\nu u} & \boldsymbol{H}_{\nu w} \\ \boldsymbol{H}_{\mu v} & \boldsymbol{H}_{\mu u} & \boldsymbol{H}_{\mu w} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{H}_{\omega w} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{v} \\ \Delta \boldsymbol{u} \\ \Delta \boldsymbol{w} \end{bmatrix} \tag{8}$$

This transformation produces the model

$$\begin{bmatrix} \Delta \boldsymbol{y} \\ \Delta \boldsymbol{\nu} \end{bmatrix} = \begin{bmatrix} \boldsymbol{K}_{y\mu} \\ \boldsymbol{K}_{\nu\mu} \end{bmatrix} \Delta \boldsymbol{\mu} + \begin{bmatrix} \boldsymbol{K}_{y\omega} \\ \boldsymbol{K}_{\nu\omega} \end{bmatrix} \Delta \boldsymbol{\omega} \tag{9}$$

where the gains are given by

$$\begin{bmatrix} \boldsymbol{K}_{y\mu} \\ \boldsymbol{K}_{\nu\mu} \end{bmatrix} = \begin{bmatrix} \boldsymbol{K}_{yu} \\ \boldsymbol{H}_{\nu u} + \boldsymbol{H}_{\nu v}\boldsymbol{K}_{vu} \end{bmatrix} (\boldsymbol{H}_{\mu u} + \boldsymbol{H}_{\mu v}\boldsymbol{K}_{vu})^{-1} \tag{10a}$$

$$\begin{bmatrix} \boldsymbol{K}_{y\omega} \\ \boldsymbol{K}_{\nu\omega} \end{bmatrix} = \left\{ \begin{bmatrix} \boldsymbol{K}_{yw} \\ \boldsymbol{H}_{\nu w} + \boldsymbol{H}_{\nu v}\boldsymbol{K}_{vw} \end{bmatrix} - \begin{bmatrix} \boldsymbol{K}_{y\mu} \\ \boldsymbol{K}_{\nu\mu} \end{bmatrix} (\boldsymbol{H}_{\mu w} + \boldsymbol{H}_{\mu v}\boldsymbol{K}_{vw}) \right\} \boldsymbol{H}_{\omega w}^{-1} \tag{10b}$$

Equation 10a is derived in Häggblom and Waller (1988) and Eq. 10b can be analogously derived (Häggblom, 1988).

The disturbances entering the process are input variables that are not used as manipulators to control the process. Therefore, it is usually meaningless to transform such input variables, and the transformation matrix $\boldsymbol{H}_{\omega w}$ is then equal to the identity matrix. $\boldsymbol{H}_{\omega w} = \boldsymbol{I}$ is used in the following.

Examples of the matrices $\boldsymbol{H}$ for some control structure transformations are given in Häggblom and Waller (1988).

Structures for Disturbance Rejection and Decoupling (DRD)

Equations 7 to 10 give the machinery necessary for transformations between arbitrary control structures, such as (L, V) into (D, V).

In addition to transformations between specific structures, however, Eq. 10 can also be utilized to obtain structures with specific properties. Obviously, a structure which would be insensitive to disturbances (in the steady state), that is, a structure with

$$K_{y\omega} = O \tag{11}$$

would be interesting. Further, it would be of interest to have the structure noninteracting at the same time, that is,

$$K_{y\mu} = I \tag{12}$$

when the scaling of the input variables is suitably chosen. Such a control structure can be derived as follows. If Eq. 12 is inserted into the upper part of Eq. 10a, we obtain

$$H_{\mu u} + H_{\mu v}K_{vu} = K_{yu} \tag{13}$$

If, further, Eqs. 11 and 12 are combined with the upper part of Eq. 10b, we obtain

$$H_{\mu w} + H_{\mu v}K_{vw} = K_{yw} \tag{14}$$

Now, if K_{vw} is invertible, a solution is obtained for $H_{\mu w} = \mathbf{0}$. This means that the disturbances need not be measured. Equations 13 and 14 then give

$$H_{\mu v} = K_{yw}K_{vw}^{-1} \tag{15}$$

$$H_{\mu u} = K_{yu} - K_{yw}K_{vw}^{-1}K_{vu} \tag{16}$$

Equation 8, with $H_{\mu w} = \mathbf{0}$, gives the definition of the new primary manipulators μ:

$$\Delta\mu = H_{\mu u}\Delta u + H_{\mu v}\Delta v \tag{17}$$

The secondary manipulators v are not changed.

As these equations show, information about the disturbances w is contained in v through K_{vw}; and when this matrix can be inverted, this information is brought over to the new manipulators μ through $H_{\mu v}$. If $v = [D\ B]^T$, it means that D and B contain information about the disturbances (e.g., in F and z).

No matter what μ is, the manipulators that physically affect the compositions in the distillation process are L and V. As the original control structure described in Eq. 7 is the (L, V) structure, $u = [L\ V]^T$. These variables can then be calculated from Eq. 17 as

$$\Delta u = H_{\mu u}^{-1}(\Delta\mu - H_{\mu v}\Delta v) \tag{18}$$

where the values of $\Delta\mu$ are given by the composition controllers and the values of Δv are measured.

Application

The control structure derived above is tested by simulation of a 15-plate pilot-plant ethanol-water distillation column for which experimental models have been obtained for four control structures (Waller et al., 1988b). In this paper reconciled parameter values, given in Waller et al. (1988a), are used. The nominal steady state at which the column was operated during the experiments is given in Table 1 (Waller et al., 1988a).

Table 1. Nominal Steady-State Data

Feed flow rate, F	200 kg/h
Distillate flow rate, D	60 kg/h
Bottoms flow rate, B	140 kg/h
Feed composition, z	30 wt. %
Distillate composition	87 wt. %
Bottoms composition	5 wt. %
Reflux flow rate, L	60 kg/h
Steam flow to reboiler, V	72 kg/h
Feed temperature	65°C
Reflux temperature	62°C

The steady-state part of the model for the (L, V) structure is

$$K_{yu} = \begin{bmatrix} -0.045 & 0.048 \\ -0.23 & 0.55 \end{bmatrix} \quad K_{yw} = \begin{bmatrix} -0.001 & 0.004 \\ -0.16 & -0.65 \end{bmatrix}$$

$$K_{vu} = \begin{bmatrix} -0.61 & 1.35 \\ 0.61 & -1.35 \end{bmatrix} \quad K_{vw} = \begin{bmatrix} 0.056 & 1.08 \\ 0.944 & -1.08 \end{bmatrix}$$

Actually, only the first rows of the matrices K_{vu} and K_{vw} are given in Waller et al. (1988a). The second rows are obtained by use of the consistency relations in Eq. 6.

The new manipulators, which result in steady-state disturbance rejection and noninteraction, are defined by Eq. 17. Numerically, we obtain

$$\Delta\mu_1 = -0.043\Delta L + 0.043\Delta V + 0.0025\Delta D - 0.0012\Delta B \tag{19a}$$

$$\Delta\mu_2 = -0.60\Delta L + 1.36\Delta V - 0.73\Delta D - 0.13\Delta B \tag{19b}$$

The values of the physical manipulators L and V are calculated according to Eq. 18 which gives

$$\Delta L = -42\Delta\mu_1 + 1.3\Delta\mu_2 + 1.1\Delta D + 0.12\Delta B \tag{20a}$$

$$\Delta V = -18\Delta\mu_1 + 1.3\Delta\mu_2 + 1.0\Delta D + 0.14\Delta B \tag{20b}$$

Figure 4 shows the simulated "open-loop" responses of the disturbance rejection and decoupling (DRD) structure to a step disturbance in the feed composition. The best two of the four control structures in Figure 3 are also included. As shown, the DRD control structure is much less sensitive to the disturbance than the other control structures, especially in the stripping section. However, there are small (open-loop) steady-state offsets also for the DRD strategy. This is due to round-off errors in the coefficients for ΔD and ΔB in Eq. 20. If the gain matrix

$$\begin{bmatrix} 1.1 & 0.12 \\ 1.0 & 0.14 \end{bmatrix} \tag{21}$$

in Eq. 20 is replaced by

$$\begin{bmatrix} 1.066 & 0.116 \\ 1.002 & 0.144 \end{bmatrix} \tag{22}$$

the offsets are strongly reduced, as shown by Figure 5.

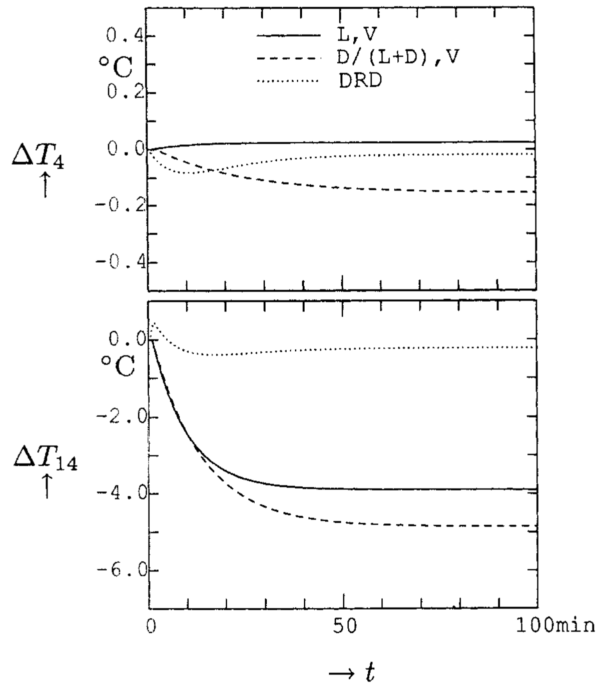

Figure 4. Simulated "open-loop" responses to a 6 wt.% disturbance in feed composition.

Process model for DRD given by Eqs. 23, 24 and 25.

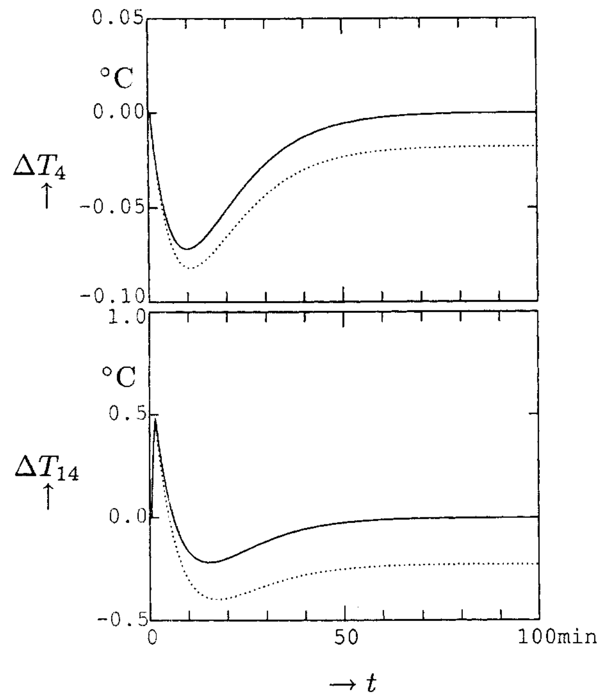

Figure 5. Sensitivity of DRD strategy to parameter variations.

Dotted lines show the "open-loop" responses to a step disturbance in the feed composition when the parameter values in Eq. 1 are used; full lines show the responses when the parameter values of Eq. 22 are used. Process model as in Figure 4.

During feedback control of the primary outputs (compositions or temperatures) this parameter sensitivity is, of course, less important. Figure 6 shows the closed-loop responses of the three strategies to a step disturbance in the feed composition. As shown, the new structure responds differently to the disturbance than do the other two structures. However, in this example with carefully tuned feedback controllers, the control quality is about the same for the DRD strategy as for the best two of the previously studied strategies (Waller et al., 1988b). The important difference lies in the fact that the importance of feedback is much smaller for the DRD structure than for the other structures studied. The integrity (robustness with respect to composition or temperature controller failure) is high for the DRD structure: the disturbances for which the DRD structure is designed are largely eliminated even in the case of failure of one or both of the primary feedback controllers.

The process model used for the DRD simulations in Figures 4 to 6 is

$$\begin{bmatrix} \Delta y \\ \Delta x \end{bmatrix} = G_{yu} \begin{bmatrix} \Delta L \\ \Delta V \end{bmatrix} + G_{yw} \begin{bmatrix} \Delta F \\ \Delta z \end{bmatrix} \tag{23a}$$

$$\begin{bmatrix} \Delta D \\ \Delta B \end{bmatrix} = G_{vu} \begin{bmatrix} \Delta L \\ \Delta V \end{bmatrix} + G_{vw} \begin{bmatrix} \Delta F \\ \Delta z \end{bmatrix} \tag{23b}$$

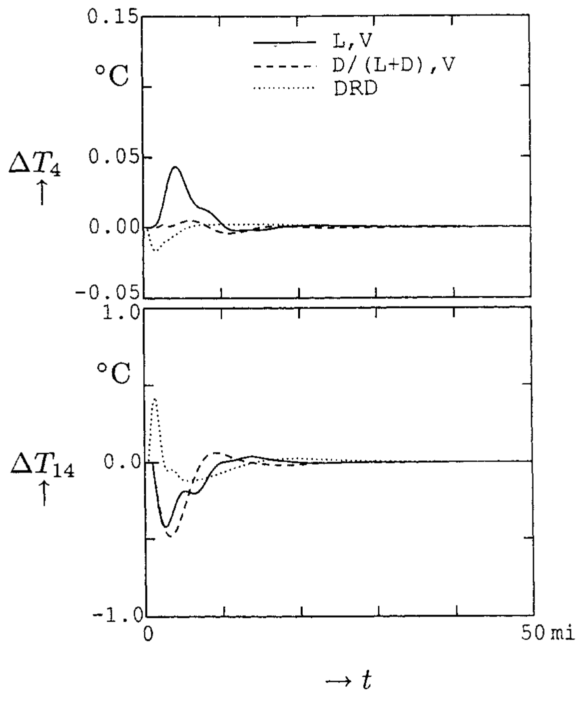

Figure 6. Feedback control of 6 wt.% step disturbance in feed composition.

Settings of feedback PI-controllers (reset times in minutes):

	$K_{c,top}$	$T_{R,top}$	$K_{c,bottom}$	$T_{R,bottom}$
(L, V)	−130	1.6	13	1.6
$(D/(L+D), V)$	0.76	1.6	13	1.6
DRD	4.5	1.7	3.5	3.3

with

$$G_{yu} = \begin{bmatrix} \dfrac{-0.045e^{-0.5s}}{8.1s + 1} & \dfrac{0.048e^{-0.5s}}{11s + 1} \\ \dfrac{-0.23e^{-1.5s}}{8.1s + 1} & \dfrac{0.55e^{-0.5s}}{10s + 1} \end{bmatrix} \tag{24a}$$

$$G_{yw} = \begin{bmatrix} \dfrac{-0.001e^{-1.5s}}{10s + 1} & \dfrac{0.004e^{-1.0s}}{8.5s + 1} \\ \dfrac{-0.16e^{-1.0s}}{5.5s + 1} & \dfrac{-0.65e^{-1.0s}}{9.2s + 1} \end{bmatrix} \tag{24b}$$

and

$$G_{vu} = \begin{bmatrix} -0.61 & 1.35 \\ 0.61 & -1.35 \end{bmatrix} \tag{25a}$$

$$G_{vw} = \begin{bmatrix} 0.056 & 1.08 \\ 0.944 & -1.08 \end{bmatrix} \tag{25b}$$

In G_{yu} and G_{yw} the time constants and dead times are expressed in minutes. The gains contain the units kg/h, wt. %, and °C.

In reality, there is dynamics also in G_{vu} and G_{vw}. In order to make a comparison as accurate as possible between simulations and experiments, the transfer functions G_{vu} and G_{vw} were identified to be roughly

$$G_{vu} = \begin{bmatrix} \dfrac{-0.61e^{-0.5s}}{1.0s + 1} & \dfrac{1.35e^{-0.5s}}{1.0s + 1} \\ \dfrac{0.61e^{-1.5s}}{1.5s + 1} & \dfrac{-1.35e^{-1.5s}}{1.0s + 1} \end{bmatrix} \tag{26a}$$

and

$$G_{vw} = \begin{bmatrix} \dfrac{0.056e^{-1.0s}}{4.0s + 1} & \dfrac{1.08e^{-1.0s}}{2.0s + 1} \\ \dfrac{0.944e^{-1.0s}}{1.5s + 1} & \dfrac{-1.08e^{-1.0s}}{3.5s + 1} \end{bmatrix} \tag{26b}$$

Also here the unit for time is minutes.

Simulated open-loop responses for the DRD and the (L, V) structures are shown in Figure 7, where the process model defined by Eqs. 23, 24 and 26 has been used. An experimental comparison between the DRD and (L, V) structures is shown in Figure 8. The agreement between the experimental results and the corresponding simulations (Figure 7) can be considered to be satisfactory.

Discussion

The DRD control structure is designed to be self-regulating with respect to disturbances in the feed flow rate and the feed composition. The simulations and experimental results shown in this paper confirm that the DRD structure is less sensitive (in steady state) to a disturbance in the feed composition for the column in question than four previously studied structures. The improvement is especially pronounced for the stripping section.

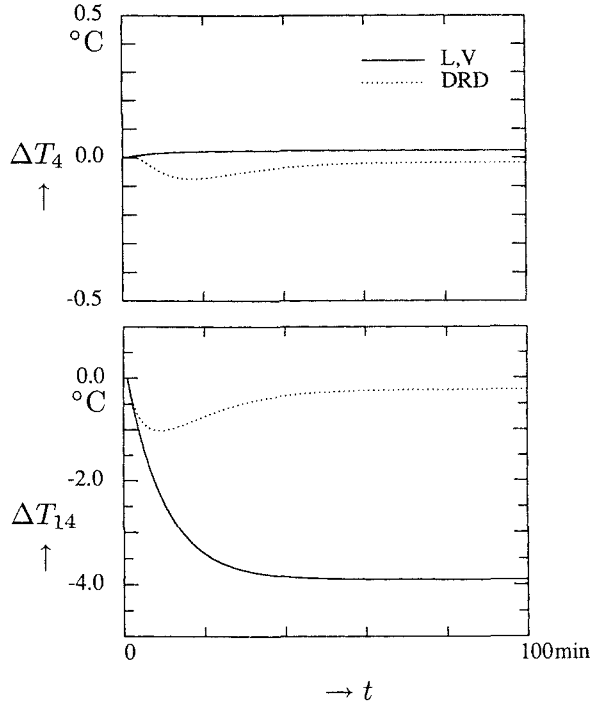

Figure 7. Simulated step responses as in Figure 4 for (*L, V*) and DRD, but using process model defined by Eqs. 23, 24 and 26 for DRD.

Similar results (but not shown in this paper) have been obtained for disturbances in the feed flow rate.

As a consequence of this, it seems possible that no (or very weak) feedback control would be needed to cope with distur-

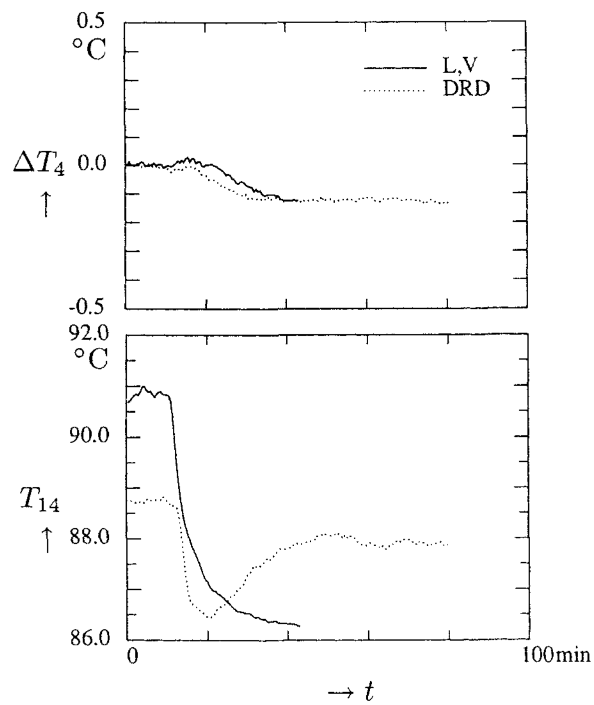

Figure 8. Experimental step responses corresponding to Figure 7.

bances in the feed flow rate and the feed composition. Further, if one of the products is on feedback control, the other could possibly be left uncontrolled without too much floating away from the setpoint. It may thus be sufficient to apply one-point control to obtain acceptable disturbance rejection of both products in a two-product distillation, especially if the uncontrolled product is an intermediate product in the plant, that is, not an end-product with stringent specifications.

The disturbances ΔF and Δz used in the DRD design above were chosen because they usually are the most important disturbances in practice. If other disturbances, like the feed enthalpy Δq, are important in addition to ΔF and Δz, the design could be performed as follows. Instead of starting from a structure like (L, V), which is sensitive to ΔF (at least in the column studied), the design could start from a structure which is quite insensitive to disturbances in F, such as $(L/F, V/F)$, $(L/F, B/F)$, and $(D/(L + D), B/F)$ (Häggblom and Waller, 1989). Then a DRD structure could be calculated for disturbances in the feed composition and the feed enthalpy, resulting in a control structure defined by Eq. 17, where $\boldsymbol{u} = [L/F, V/F]^T$ and $\boldsymbol{v} = [D/F, B/F]^T$, etc.

Some further comments on the results are:

1. The DRD structure has been designed to be noninteracting and insensitive to disturbances in the steady state. Thus no process dynamics was considered in the transformation. Figure 4 shows how strong the dynamic effects are. Naturally, they are most pronounced in the initial part of the step responses.

2. Due to this dynamic interaction, tuning of the feedback loops as separate SISO loops according to Ziegler and Nichols resulted in very oscillatory responses for the example studied. The responses in Figure 6 were obtained when the controller gains were reduced by about 50% from the Ziegler-Nichols ultimate sensitivity settings.

3. The open-loop DRD strategy is quite sensitive to parameter variations thus implying that it is also sensitive to the way the level control loops work. This is explained by Eqs. 20, 21 and 22, where D and B are level manipulators. It is mainly the steady-state values of D and B that contain information about the disturbances. The (transient) parts of D and B following from adjustments of the levels do not contain that information. It may therefore be advantageous to utilize the measured values of the levels to estimate the steady-state values of D and B which would keep the levels constant.

4. The sensitivity of the DRD strategy to the values of the level manipulators and to the parameter variations discussed above can also be affected in another way. Instead of choosing the (L, V) structure as the base structure for the derivation of a self-regulating structure, one could choose a structure which already has quite good disturbance rejection properties. Ryskamps control structure $(D/(L + D), V)$ and the two-ratio structure $(D/(L + D), V/B)$ have often been suggested to have such properties (cf. Waller et al., 1988a,b). In this case, the required corrective action from the level manipulators would be smaller. Note also that the primary manipulators would involve nonlinear functions of the physical variables, such as $D/(L + D)$ and V/B. The self-regulating structure derived from such a base structure would then also perform differently from the DRD structure derived from the (L, V) structure with respect to process nonlinearities. Finally, note that the gains of the "nonlinear" base structure could still be derived from the gains of the (L, V) structure through the transformations in Eq. 10.

5. It could further be noted that Eq. 18 is not the only way to implement the control structure defined by Eq. 17. The current (measured) value of $\boldsymbol{u}$ could also be utilized in the calculation of the adjustment of $\boldsymbol{u}$. Such a solution is most easily derived directly from the model for the base structure.

A steady-state estimate of the disturbance $\Delta \boldsymbol{w}$ at time k in Eq. 7 is given by

$$\Delta \hat{\boldsymbol{w}}(k) = \boldsymbol{K}_{vw}^{-1}[\Delta \boldsymbol{v}(k) - \boldsymbol{K}_{vu}\Delta \boldsymbol{u}(k)] \quad (27)$$

The desired control structure has the property $\Delta \boldsymbol{y} = \boldsymbol{I}\Delta \boldsymbol{\mu}$. If $\Delta \boldsymbol{y}$ is eliminated from Eq. 7 by this relation, and $\Delta \boldsymbol{w}$ is replaced by the estimate $\Delta \hat{\boldsymbol{w}}$, the corresponding adjustment of $\boldsymbol{u}$ at time $k + 1$ is given by

$$\Delta \boldsymbol{u}(k + 1) = \boldsymbol{K}_{yu}^{-1}[\Delta \boldsymbol{\mu}(k) - \boldsymbol{K}_{yw}\Delta \hat{\boldsymbol{w}}(k)] \quad (28)$$

If Eq. 27 is inserted into Eq. 28, the desired solution is obtained.

Note that the methods are equivalent from a steady-state point of view [$\Delta \boldsymbol{u}(k + 1) = \Delta \boldsymbol{u}(k)$ at steady state]. Further, if the value of $\Delta \boldsymbol{u}$ is calculated almost continuously (that is, with short sampling interval), they are also dynamically equivalent. This does not imply that the sampling interval for the composition control loops has to be short. On the contrary, it can be allowed to be quite large because of the self-regulating nature of the DRD structure.

6. Finally, it can be noted that the proposed DRD control structure actually has the structure of a true MIMO system. This is seen, for instance, from Eq. 20. During feedback control, μ_1 and μ_2 are functions of the two primary product properties (compositions or temperatures), and D and B are functions of the two inventory levels. Thus, the calculated values of L and V are functions of all four output variables.

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