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Design Modifications for Improved Controllability of Distillation Columns

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Abstract

High-purity distillation columns have several characteristics that makes them inherently difficult to control. One of the main control limitations is the strong interactions between the top and bottom of the column. In this paper we study different design modifications of the column which may improve the controllability. Design modifications considered include; introducing sidestreams, changing the number of trays and use of a feed preheater in feedback control. It is shown that some of the modifications may yield a significant reduction in the interactions as well as disturbance sensitivities.

1 Introduction

High-purity distillation columns are known to be inherently difficult to control. The main reasons are high interactions (or ill-conditioning) and high disturbance sensitivity [9]. The problem of controlling the product compositions of such columns has been studied extensively in the literature over the last decades. However, most people have considered the control of columns that are close to optimally designed from a steady-state point of view. This reflects common practice in industry; a process unit is designed for steady-state optimality and the control engineer is left with the problem of designing controllers. A good control engineer may design controllers that partly overcomes the control problems. However, in many cases the operational (dynamic) performance of the column will be poor.

In this paper we discuss possible trade-offs between steady-state optimality and controllability. Relaxing the demands for steady-state optimality may be warranted in terms of improved dynamic performance. The issue of design modifications for improved control in distillation has so far gained little attention in the literature. In this paper we consider 5 different design modifications as outlined below: 1) Wachter and Andres [12] suggested to introduce sidestreams with recycling to the feed to improve controllability of high-purity separations. In this paper we consider the effect of sidestreams with and without recycling to the feed. We find that a sidestream by itself has little effect on controllability, and if recycled to the feed no effect whatsoever. 2) Kropholler and Guesalaga [5] suggested to use a bypass in reflux, i.e. to introduce parts of the reflux further down the column. However, the bypass has no effect on interactions and disturbance sensitivity. Furthermore, when designing controllers for optimized robust performance we found that the optimal controller did not make any use of the bypass. We will therefor not pursue this idea any further. 3) Loe [6] considered the use of a feed preheater in control. His idea was that manipulation of the feed preheater in a certain way would yield reduced interaction between the top and bottom of the column. In this paper we apply a slight modification of this idea and find that the improvement in controllability may be significant. 4)In addition to the above modifications we analyze the effect of introducing extra trays in the column, i.e., overdesign. Overdesign is fairly common in industry, mainly to allow for flexibility in the operation and sometimes to overfractionate the products. In this paper we consider whether overdesign may improve the controllability of the column. 5) Another issue is the selection of which inputs to use for composition control. This is often considered as a part of the column design, but the decision made here is of vital importance for the remaining control problem. The selection of a proper configuration has been treated quite extensively in the literature over the last decade ([7], [10], [3]) and is therefore not treated in detail here.

2 Modelling

Data for the example column we will use ("Column A") are given in Table 1. The column has 40 theoretical trays (N-1 trays and a reboiler) plus a total condenser. The following modelling assumptions are used: binary separation, constant relative volatility, constant molar flows (neglected energy-balance), negligible vapor holdup, and vapor-liquid equilibrium as well as perfect mixing on each stage. Neglecting the vapor holdup implies immediate vapor flow responses throughout the column. The liquid flow-dynamics are described by a linear relation between between liquid flow L_i and liquid holdup M_i;

$$L_i = L_i^0 + (M_i - M_i^0)/\tau_L \tag{1}$$

where superscript o denotes nominal steady-state values. The hydraulic time-constant τ_L is computed from a linearized Francis weir formula

$$\tau_L = \frac{2}{3}\frac{M_{oi}}{L_i} \tag{2}$$

where M_{oi} denotes liquid over weir. We use a liquid holdup on each tray equal to $M_i/F = 0.5$ min. and assume half the liquid over weir. For the example column this yields $\tau_L = 0.063 min$. The total lag from a change in reflux to a change in the liquid flow to the reboiler becomes $\theta_L = (N-1)\tau_L = 2.46 min$.

These modelling assumptions yield a dynamic model with two differential equations per tray; one for composition and one for liquid holdup. For column A this results

Table 1. Steady-state data for distillation column example (Column A). Feed is liquid.

z_F	α	N	N_F	$1-y_D$	x_B	D/F	L/F	V/F
0.5	1.5	40	21	0.01	0.01	0.500	2.706	3.206

in a total of 82 states. In the analysis we will use linear models which are obtained by linearizing the full nonlinear models around the nominal steady-state.

We will in the following mainly consider the LV-configuration, that is, with reflux L and boilup V used for composition control. This may not be the best choice of configuration with respect to control properties [10], but it is the most widespread configuration in industry.

When considering various design modifications we always adjust the steady-state values of L and V so that $1-y_D$ and x_B remain at 0.01.

3 Analysis Tools

3.1 The Relative Gain Array

The Relative Gain Array (RGA) was originally proposed by Bristol [1] as a steady-state interaction measure, and has found widespread applications for selecting single loop pairings in decentralized control. One of the main advantages of the RGA is that it depends only on the plant model itself, and does therefor not require any preliminary controller design. This is due to an assumption of perfect control. Another advantage of the RGA is that it is scaling independent.

The RGA may easily be extended to a frequency dependent measure [2], and will in this case contain more useful information with respect to feedback control. We are primarily interested in the frequency region around the expected closed-loop bandwidth. The definition of the elements in the RGA is given by

$$\lambda_{ij} = \frac{(\partial y_i/\partial u_j)_{u_{l\neq j}}}{(\partial y_i/\partial u_j)_{y_{l\neq i}}} = g_{ij}(s)[G^{-1}(s)]_{ji} \tag{3}$$

As the elements in each row and column sums up to unity in the RGA, we only have to consider the 1,1 element for the 2x2 case.

Skogestad et.al. [10] successfully used the frequency dependent RGA for selecting control configurations for several distillation columns, and Hovd and Skogestad [4] have proven its usefulness on a more general basis.

3.2 Closed Loop Disturbance Gain

The Relative Gain Array is independent of disturbances. However, the main reason for applying feedback control in distillation is rejection of disturbances that enters the process. In the literature it has been common to consider the open-loop disturbance gains at steady-state when evaluating sensitivity to disturbances. However, one should also for disturbances put emphasis on the high-frequency behavior. In addition the direction of the disturbance effect should be considered in the multivariable case. Some disturbances may be easier to reject than others due to a good alignment with the strong input directions of the plant. Stanley et.al. [11] introduced the Relative Disturbance Gain (RDG) which takes the directions into account. For a particular disturbance z_k the RDG, β_{ik}, is defined for each loop i as the ratio of the change in u_i needed for perfect disturbance rejection in all outputs to the change in u_i needed for perfect disturbance rejection in the corresponding output y_i when all other inputs are kept constant.

$$\beta_{ik} = \frac{(\partial u_i/\partial z_k)_{y_l}}{(\partial u_i/\partial z_k)_{y_i,u_{l\neq i}}} \tag{4}$$

Hovd and Skogestad [4] suggested a measure, the Closed-Loop Disturbance Gain (CLDG), δ_{ik}, based on the RDG but which also takes the disturbance gain g_{dik} into account,

$$\delta_{ik} = \beta_{ik} g_{dik} \tag{5}$$

A matrix of CLDG's may be computed from

$$\Delta = \{\delta_{ik}\} = G_{diag} G^{-1} G_d \tag{6}$$

where G_{diag} are the diagonal elements of G. Hovd and Skogestad [4] found that this measure enters nicely into the relation between control off-set and disturbances while the RGA enters in a similar way into the relation between off-set and setpoint changes.

$$e_i \approx -\lambda_{ji}\frac{1}{g_{ji}c_i}r_j + \delta_{ik}\frac{1}{g_{ii}c_i}z_k; \quad \omega < \omega_B \tag{7}$$

This implies that $|\delta_{ik}(j\omega)|$ is approximately equal to the minimum gain , $|g_{ii}c_i(j\omega)|$, needed to reject disturbance k. For stability the required gain should not be too high. That is, small values of $|\delta_{ik}|$ are preferred. Equation 7 gives a good approximation within the bandwidth of the closed loop system when all variables are scaled to be of magnitude one.

4 RGA and CLDG for example column

The RGA for column A is shown as a function of frequency in Fig.1a. The RGA starts out at a value of 35 at steady-state but breaks off at higher frequencies and reaches a value of 1 at high frequencies. The RGA value of 1 at high frequencies is due to the liquid lag which introduces a one-way decoupling at high frequencies. The frequency where the RGA-value becomes unity is given by $\omega_1 = 1/\theta_L$ [10]. The large RGA-values implies that decouplers can not be used as part of the controller design [8].

The interactions in distillation columns operated with the LV-configuration may be understood as follows: The initial composition responses are dominated by intermixing between adjacent stages as a result of the change in L and V. Due to the lag for changes in reflux flow L the interactions are small initially. The slower part of the response is dominated by interactions between the compositions on all stages. In a well designed column without any pinches in the composition profile this results in strong interactions between the top and bottom of the column.

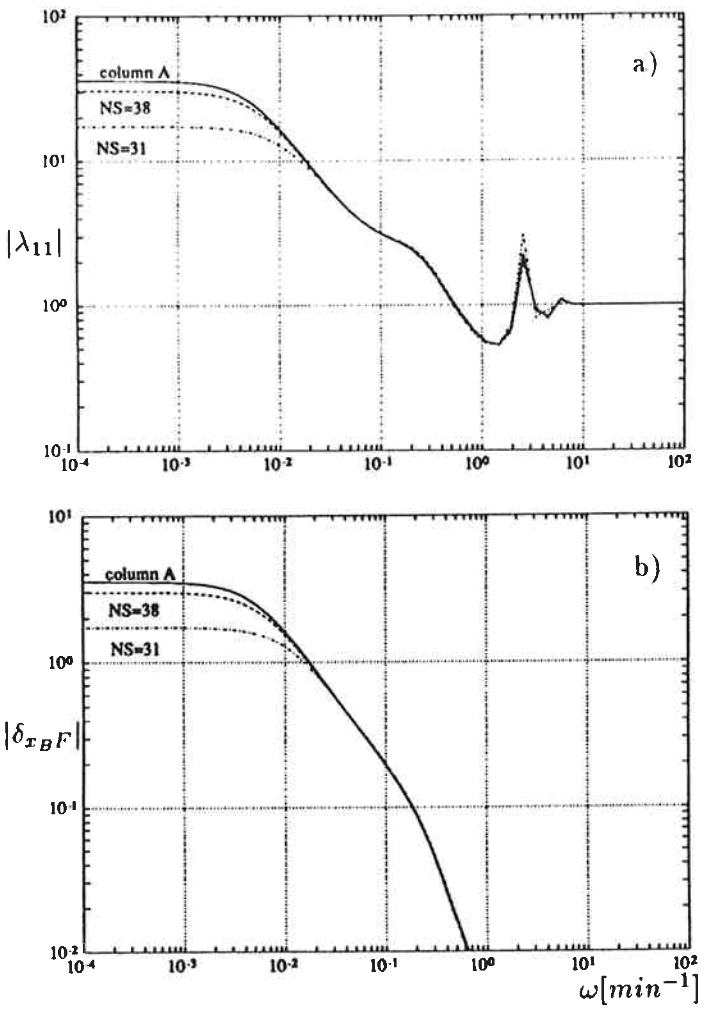

Figure 1: (a) RGA and (b) CLDG (effect of F on x_B) as a function of frequency for column A with and without sidestream. Sidestreams from tray 31 and 38 respectively.

In this paper we consider disturbances in feed flow rate F and feed composition z_F. Figure 1b shows the CLDG as a function of frequency for the effect of a disturbance in feed flow F on bottom composition x_B (worst case disturbance). We see that the CLDG has its maximum at steady-state and breaks of at the same frequency as the RGA. Note that the CLDG reflects the importance of interactions for disturbance rejection, and that the two measures are related due to this.

When analyzing systems for feedback control properties one should emphasize the frequency region around the expected closed-loop bandwidth. The expected bandwidth of most columns will be in the frequency range 0.1 - 0.01 min^{-1}, depending mainly on the size of measurement delays. We see from Fig.1 that the interactions and disturbance sensitivity are worse when the bandwidth is low.

5 Effect of sidestreams

The high interactions in high-purity distillation (using LV-configuration) is closely related to the fact that the steady-state gains for changes in internal flows ($dL = dV$) are significantly smaller than the gains for changes in external flows ($dL = -dV$) [9]. The reason for the high gains for changes in external flows is easily seen from the overall material balance (e.g., [7])

$$Dy_D + Bx_B = Fz_F \tag{8}$$

For high-purity columns we have $y_D \approx 1$ and $x_B \approx 0$ and thus $D \approx Fz_F$. Then any change in D (and B) will necessarily lead to an imbalance in Eq.8 which will strongly influence the compositions. One possible way to reduce the effect of external flows on product compositions is to withdraw a small sidestream from a plate inside the column [12]. The total material balance then becomes

$$Dy_D + Bx_B + Sx_S = Fz_F \tag{9}$$

Here S denotes the size of the sidestream and x_S the composition of the sidestream. The compositions inside the column will vary relatively much compared to the product compositions, and so a sidestream might absorb a large part of the imbalance for changes in D and B. The sidestream will only have a small effect on the gains for internal flows. This implies that we expect the RGA and CLDG to decrease with the introduction of a sidestream, at least at low frequencies.

Figure 1a shows the RGA for column A with a sidestream on tray 31 and tray 38 respectively. The sidestream was set to $S = 0.1F$ in both cases. We see that the sidestream reduces the RGA at low frequencies, but has no effect on the RGA at higher frequencies. The reduction of the RGA at low frequencies is as expected from the above discussion. The fact that the RGA is unchanged at higher frequencies is explained by the fact that the initial gains are unaffected by the sidestream; the initial responses are dominated by the intermixing between adjacent stages due to the change in flows, and as the composition profile is almost unchanged by the sidestream the initial responses are unaffected. Figure 1a shows that the effect of a sidestream on tray 31 is significantly larger than for sidestream on tray 38. The reason is that the composition changes for external flows is largest some distance away from the ends of the column.

A sidestream has a similar effect on disturbance sensitivity as on the RGA. This is illustrated in Fig.1b which shows the CLDG for a disturbance in F on x_B for column A with and without sidestreams. We see that the disturbance sensitivity is reduced at low frequencies but is unchanged at higher frequencies.

We conclude from the analysis above that although the RGA and CLDG are reduced at low frequencies by introducing a sidestream, the controllability is almost unaffected as the high-frequency behavior is unchanged. The bandwidth will usually be in the frequency range 0.1 - 0.01 min^{-1}, and in this region there is no improvement in the RGA and CLDG. For manual operation, where "control" will be slow, a sidestream may ease the operation, especially in columns with higher purities than in column A. For column A a relatively large sidestream is needed to yield a significant improvement in the low-frequency RGA, and this will be costly as the sidestream will have to be

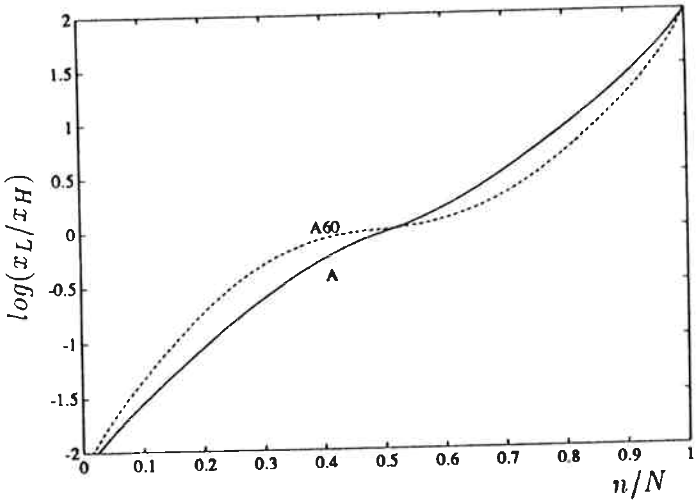

Figure 2: Plot of $log(x_L/x_H)$ against tray number (n/N) for column A and column A60.

recycled somewhere in the process. However, for columns with higher purities, a small sidestream may be rewarded with respect to manual operation. For a column with $y_D = 0.9999$ and $x_B = 0.0001$ (column F in [10]) we find that a sidestream of 1 % of the feed rate reduces the low-frequency RGA from 500 to 100.

Wachter and Andres [12] proposed to introduce a sidestream and recycle it to the feed. However, this spoils the whole idea which is to affect the overall material balance, and their solution does not yield any improvement in the RGA or CLDG whatsoever.

6 Effect of overdesign

Industrial columns are often overdesigned to increase flexibility with respect to changing feedstocks, and sometimes also to overfractionate the products so that the product specifications are easier to keep when disturbances enter the column. Here we consider whether overdesign may improve the controllability of the column.

One of the characteristics of an overdesigned column is that is has a pinch in the composition profile. This is seen when plotting $log(x_L/x_H)$ against tray number, where x_L and x_H denotes fraction of light and heavy component respectively. Figure 2 shows a plot of $log(x_L/x_H)$ for column A with 40 trays and column A60 with 60 trays (feed tray at 31) and the same product specifications as column A. We see that column A60 has a pinch in the profile around the feed, while column A has no pinch. As one of the main reasons for the interactions in distillation is the interaction between compositions on all stages, we expect the pinch zone in the overdesigned column to reduce the interaction between the sections above and below the pinch, at least at lower frequencies. An overdesign will also increase the effect of internal flows while the effect of external flows will be almost unchanged.

Figure 3a shows the RGA as a function of frequency for column A and column A60. We see that the RGA is significantly reduced at low and intermediate frequencies. The steady-state value for column A is 35 and for column A60 8.0. The initial responses are, as for the case of sidestreams, almost unchanged. However, the lag in liquid flow (θ_L) is larger for column A60 as there are more trays and the liquid flows are smaller compared to the holdups (see Eq.2). This explains the lower RGA for column A60 also at high frequencies.

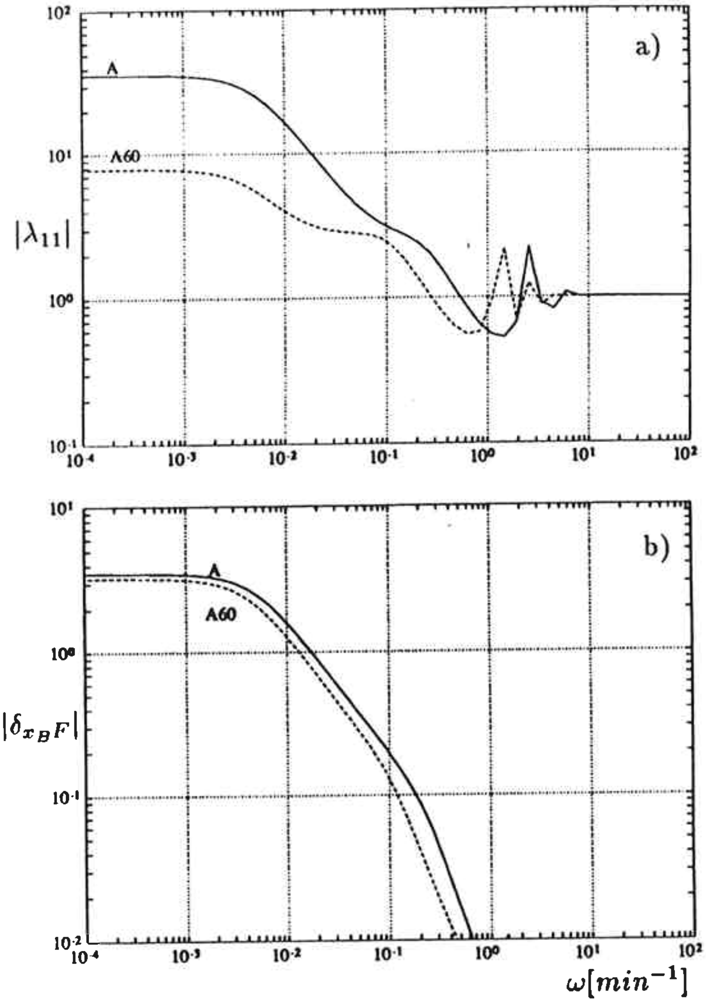

Figure 3: (a) RGA and (b) CLDG (effect of F on x_B) as a function of frequency for column A and column A60.

The effect of overdesign on disturbance sensitivity is illustrated in Fig.3b which shows the CLDG from feed flow F to bottom composition x_B. We see that the overdesign reduces the disturbance sensitivity, but the reduction is significantly less than in the RGA. This implies that although the interactions with respect to setpoint changes are decreased, we only get a slight improvement in the disturbance rejection properties. As disturbance rejection usually is the most important in process control, overdesign will in this case not yield significant improvements in performance. However, we find that the improvement in some of the elements in the CLDG for column A60 are significant (e.g., the effect of F on y_D is considerably less), and the conclusion with respect to overdesign may therefor be different for other columns.

For a column with $y_D = 0.9999$ and $x_B = 0.0001$ we find that increasing the number of trays with 50 % reduces the RGA at low frequencies from 500 to 4.0. The low RGA-values for overdesigned columns implies that the plant becomes one-way interactive, and a decoupler may yield good control performance. However, the closed-loop disturbance gains get worse, and overdesign may not improve the control performance for decentralized control.

7 Use of feed preheater in control

Many columns have a feed preheater which heats the entering feed to a desired temperature. Usually the amount of heat added is adjusted to keep the entering feed at a preset temperature, e.g., the bubblepoint temperature. However, in his thesis Loe [6] suggests that the feed preheater may be used more actively in controlling the column. By manipulating the feed preheating he argues that one may reduce the interactions between the top and bottom composition control loops. More specifically his idea is to counteract a change in boilup (V/F) by an equal change in the liquid fraction of the feed, q_F (such that $\Delta V_F = -\Delta V$ where $\Delta V_F = -F\Delta q_F$). This way a change in the boilup would have a very small effect on the flows in the top section, and one would obtain something close to a one-way decoupling of the column. However, this will require that the available change in heat input to the feed preheater is almost as large as in the reboiler. This will seldom be the case in industrial columns. Loe also discussed the possibility of using the feed preheater to control the feed-plate composition, but suggested to use a controller with integral action which obviously is not needed nor wanted; it would make the column profile extremely stiff.

Here we will modify the idea of Loe somewhat and suggest to use a pure proportional controller between the feed-plate composition (or equivalently, for a binary mixture, the temperature) and the feed preheater

$$dq_F = -k_{qF} dx_{NF} \tag{10}$$

By using a pure proportional controller one avoids making the column profile too stiff, and the controller gain may be adjusted so that the requirements for changes in the feed preheating does not exceed the available heating in the preheater. By using a feedback controller we also obtain a two-way decoupling; an increase in reflux will be counteracted by a decrease in q_F and an increase in boilup will be counteracted by an increase in q_F.

Figure 4a shows the RGA as a function of frequency for column A using different gains k_{qF} for the feed preheater control. For our example a gain k_{qF} of 1.0 implies that we require approximately 10 % change in Fq_F compared to boilup for setpoint changes. The greatest change in q_F will be for changes in feed composition; a change in z_F from 0.50 to 0.70 would yield a change in q_F from 1.0 to 0.82 (keeping y_D and x_B constant). From Fig.4a we see that the use of the preheater in control reduces the RGA for the remaining system significantly. The reduction increases with the controller gain used. With a gain of 1.0 we get a reduction in the RGA at lower frequencies from 35.0 to 4.0. The RGA is reduced at frequencies up to $0.10 min^{-1}$, but the reduction is largest at lower frequencies. This implies that we will gain most in terms of control performance when the bandwidth of the control system is small, e.g. due to large measurement delays.

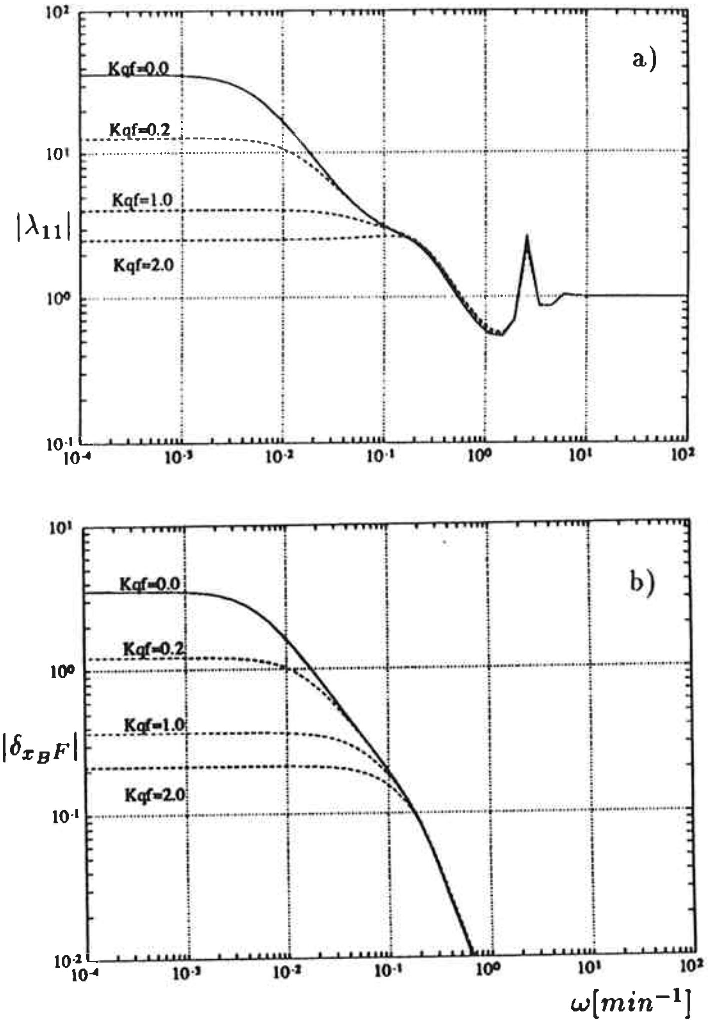

Figure 4: (a) RGA and (b) CLDG (effect of F on x_B) for column A with control of feed preheater. k_{qF} denotes gain in feed preheater controller.

The effect of the feed preheater control on disturbance sensitivity is illustrated in Fig.4b which shows the CLDG as a function of frequency for the effect of a disturbance in F on x_B. We see that we obtain similar reductions in the CLDG as obtained in the RGA.

Figure 5 shows nonlinear responses of column A to a 30 % step increase in feed rate F with and without feed preheater control ($k_{qF} = 1.0$). The composition controllers were designed for robust performance in both cases, i.e., taking uncertainties into account. A measurement delay of 3 min. was included in the design and simulations. We see that the performance is significantly improved by using the feed preheater in control. In particular we get a much faster settling to steady-state. Note that an intermediate reboiler would yield the same effect when used in control.

We have here only considered using the feed-plate composition to manipulate the feed preheating. However, it may be more advantageous to use compositions at plates some distance away from the feed-plate. For column A we find that controlling the composition on plate 31 yields a similar effect on the RGA and CLDG as in Fig.4. but with

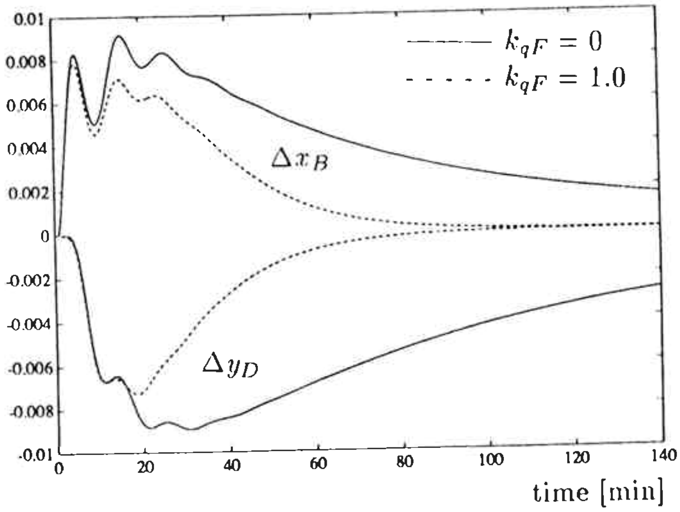

Figure 5: Nonlinear response of column A to a 30 % increase in F with and without use of feed preheater in control. Product compositions controlled by single loop PID controllers.

smaller requirements for changes in q_F.

One might believe that the utility consumption is increased significantly by using the feed preheater in control. However, the total change in heat input (i.e., $V - Fq_F$) is not increased significantly. The only exception is for large changes in feed composition. However, the heating of the feed will cost less than the heating for boilup as we have more light component in the feed.

8 Control configurations

We have in this paper only discussed the LV-configuration which is the most widespread configuration in industry. The selection of which inputs to use for composition control is made when configuring the level control system. This is often considered as a part of the column design. However, the choice made here is of vital importance for the remaining composition control problem. Different configurations will have different properties with respect to interactions and disturbance sensitivity (e.g., [7], [3], [10]). Skogestad et.al. [10] studied the control of a number of columns and found that the best choice for most columns were the ratio configuration $(L/D)(V/B)$. In many cases design modifications will not be neeeded if a proper control configuration is chosen. However, the modifications we have considered in this paper will have a similar effect on the $(L/D)(V/B)$-configuration as on the LV-configuration. For other configurations, e.g. the DV-configuration, the conclusions with respect to design modifications may be different.

9 Conclusions

1. A sidestream will reduce interactions and disturbance sensitivity at low frequencies. However, the improvements will not affect the frequency region where the expected bandwidth of the control system will be. This implies that a sidestream will only be beneficial in high-purity columns which are operated in manual mode.
2. An overdesigned column will have a pinch in the composition profile. The pinch will reduce the interactions (in terms of the RGA) in the frequency region important for feedback control. However, the reduction in disturbance sensitivity for decentralized control may be small (it may even get worse in some cases).
3. Using the feed preheater to control a composition inside the column will yield significant improvements in both the RGA and CLDG, and should be considered as a design modification for columns which are difficult to control.

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