UNIVERSITAT POLITÈCNICA DE CATALUNYA

Department of Chemical Engineering

ENERGY OPTIMISATION AND CONTROLLABILITY IN COMPLEX DISTILLATION COLUMNS

Autor: Maria Serra i Prat
Director: Miquel Perrier

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CHAPTER 6. OPTIMISING CONTROL IN THE DIVIDED WALL COLUMN

6.1 Abstract

This chapter addresses the control of the DWC energy consumption, evaluated through the boilup rate. Specifically, it addresses the control of the operating conditions that keep the boilup rate at its minimum value in presence of disturbances and uncertainties. A feedback control scheme is proposed to solve the DWC optimising control. As controlled variables, different variables that characterise optimal operating conditions are analysed. Their ability to keep operation at optimal conditions when they are kept at their nominal values is numerically evaluated. The optimal operation is also analysed in order to know the sensitivity of the objective function to the optimisation variables, and how disturbances take the operation away from optimal conditions. According to the analysis results, appropriate control structures are discussed.

6.2 Introduction

In most processes, extra operation DOF are used to optimise the steady state process operation. The optimal operation is then chosen to be the nominal operation. However, operation may be taken away from optimal conditions if disturbances and uncertainty are present. The objective of the optimising control is to maintain the process at optimal operating conditions in spite of disturbances and uncertainty. In the preceding chapters, the extra operation DOF offered by the DWC were already used to optimise the steady state operation. Stabilisation and composition control of the DWC at optimal nominal operation were studied in chapters four and five. In this chapter, the extra operation DOF offered by the DWC are used for DWC optimising control. In chapter three, it was seen that important energy savings are possible with the DWC. The importance of optimising control to maintain these savings is analysed in this chapter.

For stabilisation and composition control, setpoint values are known. Contrarily, for optimising control, the minimum boilup value changes with the operating conditions, what makes the determination of a boilup setpoint impossible. However, it is necessary to know how to move the manipulated variables in order to bring the process to optimal operation. A solution to this problem is the feedback control of a variable that characterises the optimal operation (Halvorsen et al., 1997). This approach turns the optimisation problem into a setpoint problem. The key idea is to find a measurable variable which, when kept constant at its setpoint, indirectly assure optimal operation. If this variable can be found, optimising control may be implemented through a feedback control loop. The task of searching this measurable variable is one of the main objectives of this chapter.

The search of measurable variables characteristic of the optimal operation for feedback optimising control of the DWC was considered by Halvorsen et al. (1997). Some candidate measurable variables were proposed and analysed in a qualitative way. In this chapter, a more careful evaluation is performed. A quantitative analysis is done to compare the performance of different optimising control systems facing process disturbances and model uncertainties.

The nominal operation of all the case studies studied in the chapter is the optimal operation.

6.3 Control hierarchy

In section 4.5, it was explained that solving the control of distillation processes by layers is recommended. This is the approach followed in this thesis work for the control of the DWC. In chapters four and five, the two lower control layers, stabilisation and composition control, were studied. In this chapter, the third control layer, optimising control, is studied. There is usually a time scale separation between control layers. The first control layer is the inventory control. The flow dynamics is faster than the other dynamics in the process. The second control layer is the composition control. Composition dynamics is slower than the flow dynamics, and since stabilisation is reached very quickly, composition control acts practically over a stabilised column. The optimising control is the last control layer. Weather it is interesting to try to maintain optimal operation during the composition control transitory or make optimising control act only when the composition control is achieved will be discussed in section 6.6.6.

The control hierarchy also means that in principle, to select the control structure, priority is given to the lower control layers. Therefore, the optimisation manipulated variables are the remaining ones.

6.4 Study of the optimal operation

In section 4.5, an analysis of the DWC operation DOF was done. With the considered model, the DWC had seven operation DOF. This chapter is developed using the same model, described in 4.3.1. Stabilisation and specification of the products purity (A composition in distillate, B composition in sidestream, and C composition in bottoms flowrate) use five of the operation DOF. Therefore, in a steady state DWC with specified products purity, the boilup is a function of the two remaining DOF. Equation 6.1 expresses this dependence.

$$V = V(extraDOF1, extraDOF2) \qquad (6.1)$$

From a steady state point of view, which of the seven DOF (manipulated variables) are used for the stabilisation and the composition control and which of the DOF are used for optimising control does not have any effect. If all DOF are used, the optimal operation will be achieved whatever is the task of every manipulated variable. From a control point of view, a controllability analysis will indicate the best pairings. On the contrary, if some of the manipulated variables are not used (are left constant), which are these manipulated variables will limit the achievable optimum in a different way.

6.4.1 The DWC optimum calculation

The DWC optimal operation is the steady state operation with required purities and minimum boilup. An expression for *V(extraDOF1, extraDOF2)* is not known and a DWC steady state model is not available. For this reason, the dynamic model described in 4.3.1 is used for the DWC optimisation. (In fact, since the optimisation is a steady state consideration, a modified model without liquid dynamics is used). Two optimisation procedures have been analysed. The first one considers the two extra DOF as optimisation variables. At every objective function evaluation, the DWC has to be solved. The solution is restricted by the product purities and steady state conditions. *Fsolve* function has been used to solve the restricted equation system (MATLAB, 1998). This optimisation procedure hardly succeeds because of the evaluation of non-feasible solutions. The second optimisation procedure considers all the model variables as optimisation variables and imposes the restrictions directly to the optimisation procedure. A constrained minimisation is thus used to find the DWC optimal operation. *Constr* function is used for the constrained optimisation (MATLAB, 1998). This procedure has been used for all the DWC optimisations of the thesis work.

Depending on the initial values of the optimisation variables, different solutions are found. To avoid finding local solutions close to the initial values, the *fsolve* minimum perturbation parameter has been helpful. Large minimum perturbations have been used initially to approach the optimum, and for initial values closer to the optimal values, smaller minimum perturbations have been used to obtain the optimum more precisely.

Even with initial values of the optimisation variables close to the optimal values, different solutions are found depending on the initial values. These solutions are very close to each other and they get closer changing the termination tolerances. However, solutions with boilup differences around 0.05% are already undistinguished. If these solutions correspond to real local optimums or are due to numerical problems has not been clarified.

The Hessian matrix is given as an output by the *constr* function. It could be a useful tool for the evaluation of the boilup sensitivity. However, its behaviour is very irregular. The Lagrange multipliers are also given by the *constr* function. Considering the disturbances as constrained optimisation variables, their Lagrange multipliers are obtained. The feed flowrate has normally the larger Lagrange multiplier of all the disturbances, indicating the larger influence on the boilup value.

The shape of the response surface *V(extraDOF1, extraDOF2)*, the optimal operation changes caused by the disturbances, and the variables that characterise optimal operations have a large incidence on the optimising control. These three aspects are analysed in the following sections.

6.4.2 Analysis of the response surface *V(extraDOF1, extraDOF2)*

The shape of the response surface *V(extraDOF1, extraDOF2)* has important consequences over the optimising control. The slope of the surface in the different directions indicates the sensitivity of the boilup to the optimisation variables. If the slope is small enough, optimising control may not be required. If the response surface is much wider in one direction than in another, the use of only one of the DOF for optimising control may be appropriate.

Some literature works report certain directionality of *V(extraDOF1, extraDOF2)*. As was seen in 2.6, Fidkowsli et al. (1986) found an analytical solution for the DWC optimisation. Infinite number of trays, ideal mixture, and sharp separations were assumed. The considered optimisation DOF were L_I and β. Interestingly, a set of optimal solutions was found, which could be graphically presented on the β-L_I plane as the closed segment having the ends at points *P* and *R* (see Figure 6.1). The co-ordinates of the segment ends are given in equations 6.2 to 6.7, where *A*, *B*, and *C* are the component flowrates in the feed.

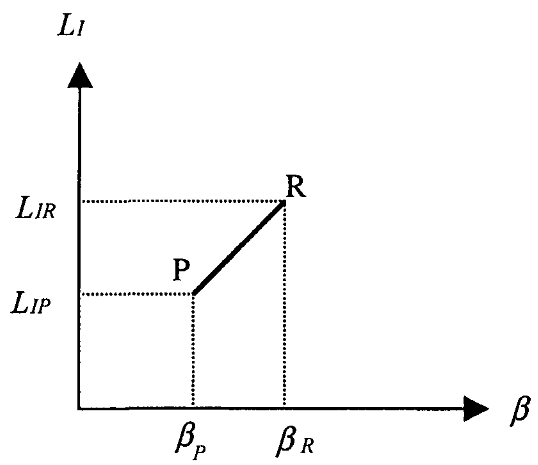

Figure 6.1: Set of optimal solutions

$$\beta_P = \frac{\alpha_B - \alpha_C}{\alpha_A - \alpha_C} \qquad (6.2)$$

$$L_{IP} = \frac{(A+B+C)\alpha_C}{\alpha_A - \alpha_C} \qquad (6.3)$$

$$\beta_R = \frac{L_{II}^{opt}(\alpha_A - \alpha_B) - A\alpha_B}{L_{II}^{opt}\alpha_A - (L_{II}^{opt} + A + C)\alpha_C} \qquad (6.4)$$

$$L_{IR} = L_{II}^{opt}\left[1 - \frac{B\alpha_A}{L_{II}^{opt}\alpha_A - (L_{II}^{opt} + A + C)\alpha_C}\right] \qquad (6.5)$$

$$L_{II}^{opt} = \max\left(\frac{A\theta_1}{\alpha_A - \theta_1}, \frac{A\theta_2}{\alpha_A - \theta_2} + \frac{\alpha_B B}{\alpha_B - \theta_2}\right) = \max\left(L_{II\varphi1}^{(1)}, L_{II\varphi2}^{(2)}\right) \qquad (6.6)$$

θ_1 and θ_2 are the roots of Underwood's equation,

$$\frac{\alpha_A A}{\alpha_A - \theta} + \frac{\alpha_B B}{\alpha_B - \theta} + \frac{\alpha_C C}{\alpha_C - \theta} = 0 \qquad (6.7)$$

As can be seen, *P* and *R* depend only on the relative volatilities and the feed composition. Therefore, depending on the relative volatilities and the feed composition, *P* and *R* define segments of different length and orientation in the β-L_I plane. There are three possibilities:

- $L_{II\varphi1}^{(1)} > L_{II\varphi2}^{(2)}$, then $0<\beta_R<\beta_P<1$
- $L_{II\varphi1}^{(1)} < L_{II\varphi2}^{(2)}$, then $0<\beta_P<\beta_R<1$
- $L_{II\varphi1}^{(1)} = L_{II\varphi2}^{(2)}$, then $\beta_R=\beta_P$, the set of optimal solutions is reduced to one point.

The existence of multiple optimal solutions in a closed segment of the β-L_I plane is very important for the optimising control. Somehow, it relaxes the need of optimising control. Specifically, it makes possible that the process get back to optimal operating conditions (when disturbances have taken it away from optimal operating conditions) moving only one of the two optimisation variables. This possibility only exists if the *P-R* segment is not parallel to any optimisation variable axe.

But β and L_I are not possible manipulated variables. To consider the use of only one manipulated variable for optimising control, the base has to be changed from β-L_I to the plane of actual manipulated variables. The position of the set of optimal solutions in the plane of actual manipulated variables will indicate if it is possible to control the optimal operation using only one of the manipulated variables. Halvorsen et al. (1999) showed that the set of optimal solutions in the *SPLITD-SPLITB* plane is also a closed segment.

The existence of multiple solutions all long the *P-R* segment happens in infinite DWC. However, with enough trays in finite DWC, a similar behaviour may be expected. Halvorsen et al. (1997) calculated *V(SPLITD, SPLITB*) around the optimal operation (nominal operation) for a finite DWC separation process. They found that the minimum boilup was almost maintained in a long narrow area in the *SPLITD-SPLITB* plane. The minimum boilup direction was not parallel to the *SPLITD* axis. This fact indicated that optimal operating conditions could be kept using only *SPLITD* as manipulated variable for optimising control. In section 6.6, the considered separation in Halvorsen et al. (1997) is chosen as case study.

6.4.3 Influence of the disturbances on the optimal operation

Disturbances may change the position of the optimal operation in the *extraDOF1-extraDOF2* plane. On the other hand, uncertainty causes that the optimal operation is not precisely localised. For optimising control, it is not only the shape of the response surface that is important, but also this shape in relation with the effect of disturbances and uncertainty. An analysis of the effect of disturbances and uncertainty on the response surface is required to consider the need of optimising control. Specifically, optimising control will be required if the expected disturbances and uncertainty cause large displacements of the response surface in a direction with large slope.

To know if satisfactory optimising control can be achieved with only one manipulated variable, the effect of disturbances and uncertainty has also to be taken into account. If with the manipulation of only one variable, it is always possible to be into the optimal displaced region, the use of only this manipulated variable can provide satisfactory optimising control.

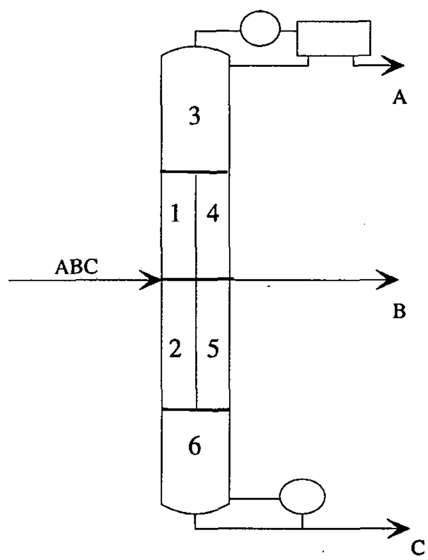

Figure 6.2: Sections of DWC

6.5 Optimal operation characterisation. Proposed controlled variables for optimising control.

Feedback control of a variable for indirect control of optimal operating conditions is a simple optimising control strategy. However, it requires the existence of a measurable variable that characterises the optimal operation. The optimal operation in a DWC corresponds to a specific distribution of separation effort between sections. Because of that, variables that characterise this distribution might be good controlled variables for feedback optimising control. As explained in 2.6.2, the separation performed in the prefractionator, determined by A, B, and C prefractionator recoveries, determines the distribution of separation effort between the DWC sections. The three recoveries can not be measured in a single measure. However, the recovery of B component may be a good representation of the distillation effort distribution. Also the recoveries of A or C may represent this distribution. Because of that, some variables related to the prefractionator recoveries are proposed as measured variables for feedback optimising control.

The following controlled variables have been considered controlled variables for the DWC feedback optimising control:

- d/F: d is the net flow from the prefractionator top to the main column. It determines the flow split in the prefractionator. Although in an imprecise way, it also determines the split of B in the prefractionator (for sharp distillations, d is closely related to the recovery of B in the prefractionator). Measurement of d would be practically difficult in a DWC, but not in a Petlyuk Column (see Figure 2.15). Using the DWC model, d is calculated as indicates equation 6.8. d/F has the same properties than d but it takes into account the feed flowrate, which is important in order to face feed flowrate disturbances.

$$d = SPLITB*V + (1-q_F)*F - SPLITD*L \qquad (6.8)$$

- ΔN and $\Delta N'$: ΔN is the number of trays between the tray from where the sidestream is withdrawn and the tray that has the largest B composition. $\Delta N'$ is the continuous variable corresponding to a cubic interpolation of the discrete variable ΔN. $\Delta N'$ is able to follow the optimum more closely. ΔN is proposed because it was observed that the tray with highest B composition was the sidestream tray in the optimal operation of different DWC distillations. Therefore, the setpoint of ΔN is 0. ΔN and $\Delta N'$ take only into account the main column. If the tray compositions are easily derived from the temperatures, ΔN will not be difficult to measure.

- *DTS* is a measure of the temperature profile symmetry at both sides of the DWC wall. It takes into account the prefractionator and the main column. Its definition is given in equation 6.9, where $T_{N,i}$ is the temperature of tray i in section N (see Figure 6.2). *DTS* is proposed because it was observed that the temperature profiles at both sides of the DWC wall were quite symmetric in the optimal operation of different DWC distillations. In the case of liquid feed and liquid sidestream product, *DTS* optimal value is close to 0. If the feed is not saturated liquid, the optimal value is greater than 0. The considered DWC model does not calculate temperature. Temperature of each tray is calculated assuming the contribution of each component with its boiling temperature to be proportional to its molar fraction. *DTS* will not be a difficult variable to measure because temperatures are easily measured.

$$DTS=\Sigma_i(T_{1,i}-T_{4,i})+\Sigma_i(T_{2,i}-T_{5,i}) \qquad (6.9)$$

- y^d_C is the C composition of the net flow from the prefractionator top to the main column. Its measurement involves composition and flow measurements.
- x^b_A is the A composition of the net flow from the prefractionator bottom to the main column. Its measurement involves composition and flow measurements.
- β is the recovery of B in the prefractionator distillate, described in equation 2.1. Its measurement involves composition and flow measurements.

6.6 Case study

To analyse optimising control in the DWC, a case study has been chosen. It consists in the distillation of a mixture with relative volatilities α=(4:2:1) in a DWC with eight plates in each section. Feed is 1 kmol/min of equimolar mixture and the required purity of the three products is 0.97 molar. The feed heat condition is optimised and the optimal feed liquid fraction is q_F=0.477. The nominal operation is defined by:

- Reflux rate L=1.68 kmol/min
- Boilup V=1.49 kmol/min
- Distillate flowrate D=0.33 kmol/min
- Bottoms flowrate B=0.334 kmol/min
- Side stream flowrate S=0.3227 kmol/min
- Split of liquid *SPLITD*=0.450
- Split of vapour *SPLITB*=0.491

The considered control structure for the lower control layers is "DB" stabilisation and *L S V* for composition control (A, B, and C products purity, respectively). Therefore, *SPLITD* and *SPLITB* are the two extra variables used for optimising control.

6.6.1 The shape of the minimum

To see how the disturbances move the response surface, the best would be to plot *V*(*SPLITD*, *SPLITB*) for non disturbed and disturbed operations. With these plots, it would be clear if optimal operation could be maintained using only one manipulated variable. However, a practical way to obtain this information, which saves a lot of computation, is to compare the optimal boilup values of the disturbed system when both optimisation variables are used, when only one of the optimisation variables is used, and when both optimisation variables stay at their nominal values (in this case, there is not optimisation and the only solution is found).

For the case study, these results are given in Table 6.1. For all the disturbed columns, the minimum boilup with *SPLITD* and *SPLITB* free (the actual optimal value) is given in the third column. The minimum boilup with *SPLITD* free and *SPLITB* fixed at the nominal value (suboptimal value) is given in the fourth column. In the last column, the boilup with *SPLITD* and *SPLITB* fixed at the nominal values is given.

SPLITD and *SPLITB* optimal values do not depend on the feed flowrate. Therefore, disturbances in F do not need optimising control when *SPLITD* and *SPLITB* are the remaining variables for optimising control. The considered disturbances are the feed composition and the feed heat condition. For each source of disturbance, some values around the nominal values have been analysed.

Table 6.1: Optimal, suboptimal and non optimised boilup of a disturbed DWC

Disturbance	Disturbance value		V optimal	V suboptimal *SPLITB* fixed	*SPLITD* fixed *SPLITB* fixed
z_A/z_B	0.3993	0.3333	1.531	1.532	1.550
	0.3333	0.3993	1.554	1.557	1.585
	0.2673	0.3333	1.482	1.482	1.510
	0.3333	0.2673	1.425	1.428	1.489
q_F	0.372		1.447	1.448	1.554
	0.425		1.472	1.472	1.498
	0.529		1.524	1.525	1.546
	0.582		1.552	1.554	1.626

Comparing the optimal boilup and the boilup with fixed optimisation variables (columns 1 and 3), 7% is the maximum difference, which is caused by a disturbance in q_F. Although results change from one case to another, DWC energy savings may be of 30%. Therefore, energy loss is moderated (or even small) when *SPLITD* and *SPLITB* are not used for optimising control and are kept constant at their optimal nominal values. Comparing the suboptimal boilup with the optimal boilup (columns 1 and 2), 0.2% is the maximum difference. Therefore, using only *SPLITD* to bring the system at optimal operation, the system is practically kept at optimal operation.

These results are in accordance with a *V(SPLITD, SPLITB)* surface with marked directionality. For any movement of the boilup surface caused by the considered disturbances, with fixed *SPLITB*, a *SPLITD* value that makes the pair (*SPLITD,SPLITB*) be close to the minimum has been found. Therefore, an optimising control structure consisting only in the manipulation of *SPLITD* optimisation variable should be appropriate.

6.6.2 Numerical comparison between different candidate feedback variables

In this section, the variables proposed in section 6.5 for feedback optimising control are analysed in order to know how well they characterise optimal operation. Their ability to maintain the DWC at optimal operation in presence of disturbances and uncertainties is numerically evaluated.

Because of the reasons given in 6.6.1, *SPLITD* has been used as manipulated variable for the optimisation loop, while *SPLITB* has been kept constant. Therefore, the control system has become a four-loop control system (considering composition and optimising control). PI controllers are used to close all control loops. By the moment, the tuning problem is let aside.

For each one of the candidate controlled variables, a set of different disturbances has been loaded and the behaviour of the controlled DWC until steady state achievement is simulated. *SPLITD* takes care that the candidate controlled variable is maintained at its nominal value. This brings the process to different steady sates for the different control structures. The boilup values of these different steady states are the object of the comparisons. A good candidate is a variable that drives the boilup very close to the suboptimal value. In Table 6.2, the results for the same disturbances in Table 6.1 are shown.

As explained, for feed flowrate disturbances, *SPLITD* should not change because its optimal value does not change with a feed flowrate disturbance. At steady state, none of the considered controlled variables depends on the feed flowrate. Because of that, they are not moved from the setpoint and *SPLITD* does not move. Therefore, for feed flowrate disturbances, all the control structures achieve the suboptimal values.

y^d_C/z_C performance has been evaluated and compared to the performance of y^d_C. Despite y^d_C/z_C is better, the improvement is small. For feed composition disturbances, in the most different cases, boilup is reduced by a 2%. Besides, a measure of the feed composition is needed. The recovery of C in the prefractionator has been also considered. Its performance is very similar to that of y^d_C/z_C.

The composition of C in tray *NCD* (see Figure 2.16) divided by z_C is also evaluated. Its behaviour is similar to the one of the C prefractionator recovery, but still a little better for feed composition disturbances.

For a disturbance in the feed composition of z_A=0.267 and z_B=0.333, if x^b_A is kept at the setpoint, no solution is found. Contrarily, controlling x^b_A/z_A, this problem is not found. Besides, with x^b_A/z_A, all the values for feed composition disturbances are improved.

Table 6.2: Steady state boilup values of disturbed operations with one DOF optimising control.

			DTS	y^d_C	β	*d/F*	$\Delta N'$	x^b_A	
Disturbance	Disturbance value		*V*	*V*	*V*	*V*	*V*	*V*	*V* suboptimal
z_A/z_B	0.399	0.333	1.602	1.560	1.536	1.630	1.566	1.586	1.532
	0.333	0.399	1.580	1.562	1.557	1.591	1.569	1.565	1.557
	0.267	0.333	1.541	1.504	1.487	1.608	1.498	-	1.482
	0.333	0.267	1.444	1.430	1.428	1.488	1.432	1.436	1.428
	0.379	0.379	1.664	1.601	1.567	1.668	1.602	1.618	1.564
	0.379	0.286	1.476	1.475	1.472	1.482	1.478	1.486	1.470
	0.286	0.379	1.532	1.532	1.529	1.533	1.526	1.589	1.526
	0.286	0.286	1.505	1.455	1.440	1.627	1.460	1.756	1.438
q_F	0.372		1.451	1.449	1.451	1.451	1.448	1.457	1.448
	0.425		1.473	1.472	1.473	1.473	1.472	1.474	1.472
	0.529		1.526	1.525	1.526	1.526	1.531	1.526	1.525
	0.582		1.557	1.554	1.557	1.557	1.558	1.56	1.554

Consequences of uncertainty in the measure of the products purity and in the measure of the controlled variables have been evaluated. Uncertainty in the measure of the products purity has been simulated changing the purity setpoint values. In the same way, uncertainty in the measure of the controlled variables has been simulated changing the controlled variables setpoint values. In Table 6.3, the results are shown.

Table 6.3: Steady state boilup values of uncertain operations with one DOF optimising control.

				DTS	y^d_C	β	*D/F*	$\Delta N'$	
Disturbance	Disturbance value			*V*	*V*	*V*	*V*	*V*	*V* suboptimal
Purity setpoint A/B/C	0.97	0.97	0.98	1.727	1.775	1.727	1.727	1.727	1.727
	0.97	0.97	0.96	1.371	1.382	1.371	1.371	1.372	1.370
	0.97	0.98	0.97	1.552	1.552	1.556	1.556	1.553	1.552
	0.97	0.96	0.97	1.467	1.467	1.469	1.469	1.468	1.467
	0.98	0.97	0.97	1.564	1.584	1.569	1.569	1.568	1.564
	0.96	0.97	0.97	1.466	1.470	1.467	1.467	1.467	1.466
% error in setpoint	10			1.499	1.500	1.512	1.590	1.504	
	-10			1.499	1.499	1.513	1.593	1.498	

6.6.3 Results

Analysing the results of all simulations and optimisations, the following can be concluded:

- *d/F* is not a good feedback variable. It brings the system close to the optimum for setpoint changes and for disturbances in q_F. However, it behaves very bad in front of feed composition disturbances, worst than fixing *SPLITD* at the nominal value.

- β, together with y^d_C, has the best behaviour in front of feed composition disturbances. It is much better than *d/F*, what indicates that the sharp distillation assumption is inappropriate (*d/F* and β would be equivalent for sharp distillations). It has an acceptable behaviour in front of feed vapour fraction disturbances. In front of uncertainty in product compositions, it is almost as good as *DTS*, the best one in this case. Finally, robustness against bad measurement is acceptable.

- ΔN has the problem that only indicates *SPLITD* to change when the changes in profile are large because of the discreteness of the variable. $\Delta N'$ is better than ΔN. Other variables are better than $\Delta N'$ for the considered disturbances and uncertainties. However, it is the best of all the controlled variables for larger changes in feed composition.

- *DTS* is the best feedback variable for uncertainty in the product compositions and uncertainty in its self value. Its behaviour in front of feed composition and vapour fraction disturbances is not bad.

- y^d_C has shown to be a good feedback variable, too. Facing feed vapour fraction disturbances it is the best variable. With β, it is the best variable for disturbances in feed composition. Its behaviour in front of uncertainty in its self value is almost as good as for the *DTS* variable, which has the best behaviour. But its behaviour in front of uncertainty in the product compositions is not very good.
- y^b_A has no solution for some disturbances. Therefore, it is not a good feedback variable. Reasonably however, this result is specific of the case study and for other cases, y^b_A may be better than y^d_C.

Comparing the steady state of the controlled systems (Tables 6.2 and 6.3) with the final values without control (last column of Table 6.1), it is seen that, for all the controlled variables, there is some disturbance for which it is better to leave *SPLITD* constant than change it in order to maintain the controlled variable at setpoint. This indicates that none of the controlled variables is an exact characteristic of the optimal operation. However, three of them will give a satisfactory optimising control in a feedback control scheme. They are β, *DTS* and y^d_C. For feed composition disturbances, β is the variable that maintains V closer to the minimum, however *DTS* and y^d_C have also acceptable results. Facing feed vapour fraction disturbances, y^d_C is the best of the three but the other two are not far from it. Facing uncertainty in the product compositions, *DTS* is again the best feedback variable, being β very close and y^d_C the worst of them. Finally, *DTS* and y^d_C behave better than β in front of uncertainty in the measurements of themselves.

In a real case, the selection of one of the three variables would depend on the information about the disturbances. For instance, if a lot of disturbances were expected in the feed composition, then β would be selected. Also technical aspects should be considered. In this sense, as already explained, *DTS* can be calculated with only temperature measurements, which is a great advantage. On the contrary, the measurement of y^d_C and β involves composition and flow measurements, which are more complicated. In a DWC, the measurement of y^d_C and β variables would require the composition analysis of internal streams. On the contrary, in a Petlyuk column, those streams are external, which would be advantageous.

6.6.4 Feedforward control

Using β, y^b_A/z_A, or y^d_C/z_C as controlled variables for feedback optimising control, a measure of the feed composition is required. Strictly, feedback control does not use measurements of the input variables. In this sense, the control of β, y^b_A/z_A, and y^d_C/z_C is feedforward. Dynamically, the measure of input variables has the advantage that control action can be anticipated.

In this section, a feedforward control structure is proposed to maintain the boilup at optimum value. In this case, all the measured variables are inputs. The idea is still to find a measurable variable which is characteristic of the optimal operation. In this case, $\gamma=B4/S$ is proposed, where *B4* is the net flow down section 4 (see Figure 6.2). γ is a difficult variable to measure and thus, a bad controlled variable candidate. However, at steady state, γ can be calculated from input variables. Equations 6.10 and 6.11 express the dependence of γ on the input variables. Equation 6.12 isolates the manipulated variable, *SPLITD*. Finally, 6.13 computes the value of *SPLITD* that make γ be constant at $\gamma 0$, the nominal value.

$$B4 = \gamma * S = L - (1\text{-}SPLITD)*L - V + (1\text{-}SPLITB)*V \quad (6.10)$$

$$\gamma * S = L*SPLITD - V*SPLITB \quad (6.11)$$

$$SPLITD = \gamma * S/L + SPLITB * V/L \quad (6.12)$$

$$SPLITD = \gamma 0 * S/L + SPLITB0 * V/L \quad (6.13)$$

Using *SPLITD* as manipulated variable for optimising control obeying the command law in 6.13, very good steady state results are obtained. Better than for any of the candidate feedback variables. Results for feed disturbances and uncertainty are shown in Tables 6.4 and 6.5. This optimising control strategy will not have the simplicity of feedback control, and *S*, *L*, and *V* measurements will be required. On the other hand, anticipation characteristic of feedforward control will permit performance improvement.

Table 6.4: Steady state boilup values of disturbed operations with one DOF optimising control

			γ	
Disturbance	Disturbance value		*V*	*V* suboptimal
z_{FA}/z_{FB}	0.399	0.333	1.538	1.532
	0.333	0.399	1.557	1.557
	0.267	0.333	1.490	1.482
	0.333	0.267	1.428	1.428
	0.379	0.379	1.569	1.564
	0.379	0.286	1.473	1.470
	0.286	0.379	1.530	1.526
	0.286	0.286	1.442	1.438
q_F	0.627		1.451	1.448
	0.575		1.473	1.472
	0.471		1.526	1.525
	0.418		1.557	1.554

Table 6.5: Steady state boilup values of uncertain operations with one DOF optimising control

				γ	
Disturbance	Disturbance value			*V*	V suboptimal
Purity setpoint A/B/C	0.97	0.97	0.98	1.727	1.727
	0.97	0.97	0.96	1.371	1.370
	0.97	0.98	0.97	1.554	1.552
	0.97	0.96	0.97	1.468	1.467
	0.98	0.97	0.97	1.567	1.564
	0.96	0.97	0.97	1.466	1.466

6.6.5 Change of example

Table 6.6: Optimal, suboptimal and not optimised boilup of a disturbed DWC

Disturbance	Disturbance value		*V* optimal	*V* suboptimal *SPLITB* fixed	*SPLITD* fixed *SPLITB* fixed
z_A/z_B	0.3993	0.3333	1.713	1.718	1.736
	0.3333	0.3993	1.750	1.751	1.764
	0.2673	0.3333	1.642	1.641	1.697
	0.3333	0.2673	1.573	1.578	1.592

In 5.9.2, the separation of a mixture with α=(4.65:2.15:1) into 0.99 pure products at optimal operation was studied. The DWC design had been determined through the procedure described in 2.6.2 with *RR/MRR*=1.2. Interesting controllability indexes were found. The considered control structure was "DB" inventory control and *L S V* composition control. Therefore, *SPLITD* and *SPLITB* are the two extra variables that remain for optimising control. Solving the DWC for different *SPLITD-SPLITB* pairs, the shape of *V*(*SPLITD, SPLITB*) is found to present a marked directionality, oblique to *SPLITD* and *SPLITB* axes, as found for the base case study. Results of optimal operation for different disturbed systems can be seen in Table 6.6. For disturbances in

feed composition, the differences between optimal solution, suboptimal solution, and the solution fixing both optimisation DOF are small. In the worst direction, 3% of boilup increment. This indicates that *SPLITD* and *SPLITB* are ratios that also characterise the optimal operation to some extent.

6.6.6 Tuning of the optimising control loop and simulations

For a DWC with feedback optimising control, does it make sense to tune the optimisation loop tightly? Or it is better that the optimising control acts over the composition controlled DWC? As indicated in 6.3, there is usually a time scale separation from the optimising control loop to the faster lower layers. In this section, the tuning of the optimising control loop is discussed.

As indicated, V is the manipulated variable for the control of C composition.

Assuming a perfect controlled variable for the characterisation of optimal operation, the following reasoning is done: during the composition control transitory, to have the controlled variable at setpoint does not mean to have the boilup at its steady state controlled value. Since the boilup is the manipulated variable to control the composition of C, the boilup is given by the control law and depends on C product composition. However, it would be a good thing to optimise the boilup already in the transitory, when the compositions are still oscillating. Would this be achieved by tuning the optimisation control tightly? Before the disturbance appears, at the initial steady state, the operation is optimal when the controlled variable is at setpoint. After a disturbance is loaded, at a final steady state, the operation is optimal when the controlled variable is at setpoint. Then, reasonably, the process will be optimal during the transitory if the controlled variable is at setpoint. Therefore, tight tuning of the optimising control loop will make the boilup lower during the transitory.

In Figures 6.3 and 6.4, some simulation results are shown for the case study in section 6.6. They correspond to an optimising control structure consisting in the control of y^d_C. A disturbance in the heat feed condition is loaded, being the disturbed value q_F=0.471. The tuning of the three composition controllers is K_c=4 τ_c=50 min (L-x_{AD} loop), K_c=-10 τ_c=50 min (S-x_{BS} loop), and K_c=4 τ_c=50 min (V-x_{CB} loop). Three different tunings of the optimising control loop are compared. The reset time constant of the controllers are different. In one case, K_c=–1, τ_c=10 min, in a second case, K_c=-1, τ_c=25 min, and in the third case, K_c=–1, τ_c=100 min. In Figure 6.3, the composition profiles are shown and in Figure 6.4, the boilup profiles are shown. Simulation results show that effectively, for tighter tunings (blue line, followed by red line), the boilup is lower for all the transitory.

It has been seen that a tightly tuned optimisation control loop minimises the boilup during the transitory. Thus, from an optimisation point of view, tightly tuned loops are preferred. However, normally, the composition control is more important than the optimisation control. Because of that, it is interesting to study the influence of closing the optimisation loop on the composition control.

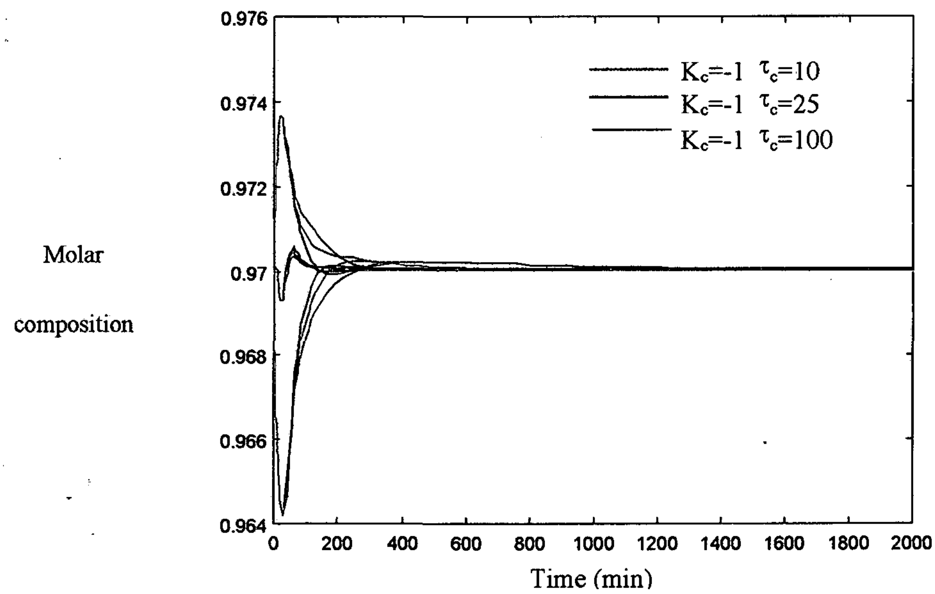

Figure 6.3: Composition profiles of a controlled DWC with a disturbance in q_F

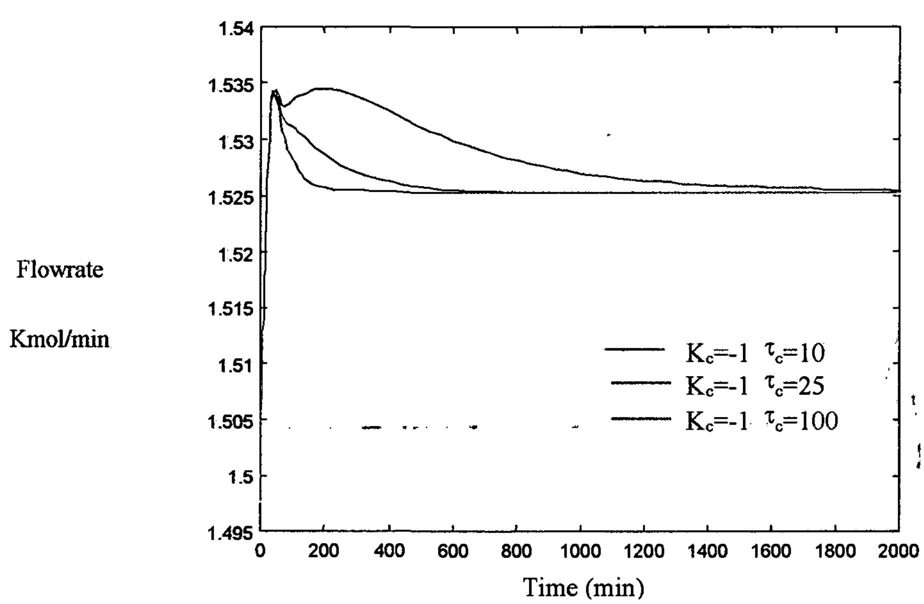

Figure 6.4: Boilup profiles of a controlled DWC with a disturbance in q_F

The effect the optimisation control loop over the composition control performance has been analysed. It has been found that whether closing the optimisation loop has a good or a bad influence on the composition control performance depends on the disturbances, their magnitude, and the tuning. For a given tuning, there are some disturbances for which closing the optimisation loop improves the composition control and there are other disturbances for which closing the optimisation loop makes the composition control worse. There are also some disturbances for which closing the optimisation loop favours the control of some product compositions and makes worse other product compositions.

If a linear system is considered to simplify, closing the optimisation loop will favour a composition loop in the following cases:

- when the disturbance makes the composition and the feedback variable move towards the same direction, if the gain of the composition over *SPLITD* has the same sign as the gain of the feedback variable over *SPLITD*.
- when the disturbance makes the composition and the feedback variable move towards opposite direction, if the gain of the composition over *SPLITD* has opposite sign as the gain of the feedback variable over *SPLITD*.

An example where optimising control is negative for the composition control is shown in Figure 6.5. Control structure and tuning of composition loops are the same than for the example in Figures 6.3 and 6.4. The tuning of the optimisation controller is K_c=–1 τ_c=50 min. A disturbance in A feed composition is applied. The disturbed composition value is z_A=0.3993. In the figure, profiles with the optimising control loop open and closed are plot. It can be seen that, although changes are not very important, closing the optimisation control loop (red lines) makes the composition profiles behave worse.

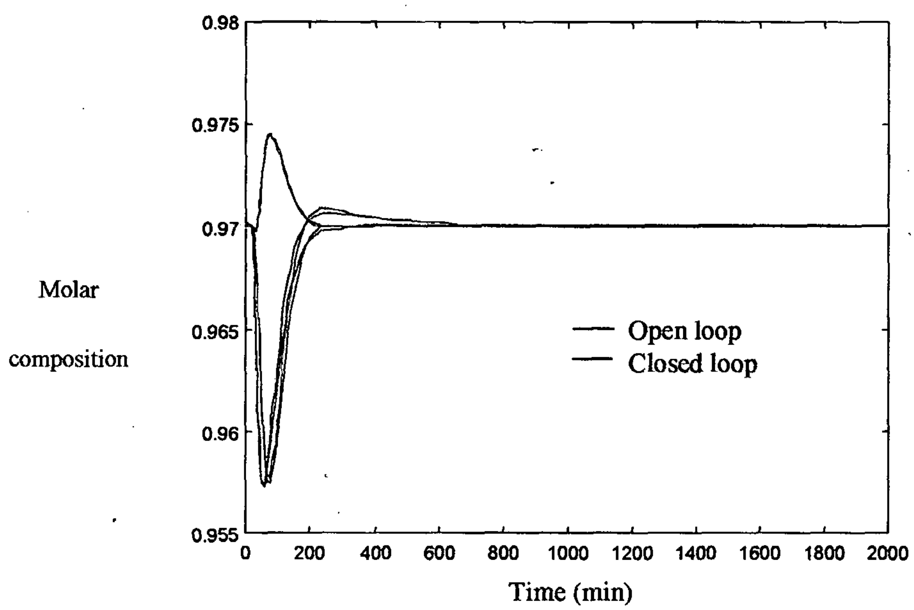

Figure 6.5: Composition profiles with a disturbance in z_A

In Figure 6.6, another example is shown. In this case, closing the optimisation loop makes the composition profiles behave better. A disturbance in the heat condition is applied, being the disturbed value q_F=0.573. Control structure and tuning of composition loops are the same than in the previous example. It is interesting to see that with closed optimisation control loop (red profiles), higher A and C compositions in the transitory are obtained, while the boilup is lower.

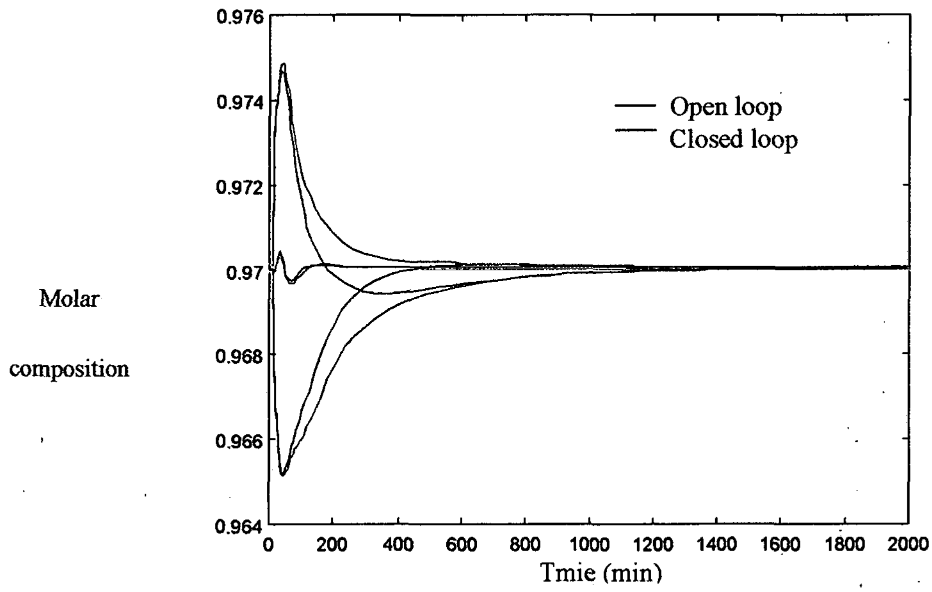

Figure 6.6: Composition profiles with a disturbance in q_F

In general, composition control has priority over optimisation control. The tuning of the optimisation control has to be chosen loose enough to not affect the composition control. As has been seen, the composition control performance will be improved by closing the optimisation loop in some cases and will be worse in other cases. However, the influence of the optimisation control loop on the composition profiles is not very important. Because of that, it may be interesting to tune the optimisation loop tightly in order to have less boilup consumption even though some composition profiles may get worse.

6.7 Other control structures

As has been seen, taking advantage of the shape of *V(SPLITD, SPLITB)* with a marked directionality, the control of the DWC may be done using six of the seven manipulated variables. Because of the difficulty to manipulate *SPLITB* in practice, this is the most appropriate variable to be non-manipulated. Being the nominal operation the operation with minimum boilup, the boilup has to be necessarily one of the manipulated variables because with fixed boilup, disturbances would make the DWC unable to fulfil the product purities, and evidently, unable to track setpoint changes.

Results of chapter four were that the preferred sets of manipulated variables for DWC at optimal operation do not include *SPLITD* and *SPLITB*. According to this, and giving preference to the control structures of the lower control levels, the remaining variables to be used for optimisation purposes are *SPLITD* and *SPLITB*. Being *SPLITB* difficult to manipulate, *SPLITD* becomes the preferred manipulated variable for optimising control.

The only control structure considered in this chapter up to now is the "DB" inventory control with *L S V* composition control, and *SPLITD* variable used for the optimisation control. In chapter four it was seen that "LV" inventory control and *D S B* composition control had good controllability properties. Both control structures are compared with *SPLITD* used for the optimisation control. The chosen example is the separation described in 4.11 of a mixture with relative volatilities α=(4.65:2.15:1) into 0.99 purity products. For this example, it is also found that there is an optimal region oblique to the *SPLITD* and *SPLITB* axes. Controlled steady state is the same for both control structures, but not the transitory. With tight tuning of the optimising control loop, the fact that *V* is the manipulated variable to control composition of C in one case and the level of the reboier in the other has a small influence on the freedom of *V* to be close to the minimum value during the transitory. The performance of optimising control was not much affected by the control structure in the lower control layers.

6.8 Typical optimisation control strategy

Typically, optimising control consists of a supervisory optimiser in a top control layer, which sends calculated optimal sepoints to the lower control layers. A model of the system is needed to calculate the optimal setpoints. There is usually a time scale separation from the optimising control loop to the faster lower layers. This means that the setpoints are updated only periodically. The approach treated in this chapter of feedback optimising control has some advantages over the typical approach. The optimising control consists in an added control loop in a MIMO diagonal feedback control strategy. The simplicity of feedback control, which does not need a model, is an advantage. On the other hand, the optimisation control actuates in a continuous way.

6.9 Conclusions

In the DWC, controlling the purity of the three products, two manipulated variables remain for optimisation purposes. Through optimising control, it is possible to maintain the DWC operation at optimal conditions (or close to it) in spite of disturbances and uncertainty.

For optimising control, the shape of the response surface (boilup) is very important. For the DWC, this surface normally presents a marked directionality such that optimal conditions are kept all over a long area. This result relaxes the need of optimising control making possible to maintain the DWC close to optimal operation using only one of the optimisation DOF.

Because control structures with best controllability for DWC at optimal operation use *L*, *D*, *V*, *B*, and *S* for stabilisation and composition control, the remaining variables for optimising control are *SPLITD* and SLPITB. Since *SPLITB* would be very difficult to manipulate, *SPLITD* is the proposed manipulated variable for optimising control.

SPLITD and *SPLITB* characterise the optimal operation to some extent. Because of that, only moderate energy losses are obtained if they are not used for optimising control. However, optimising control may reduce the energy consumption of a DWC in presence of disturbances and uncertainties.

Feedback control of a variable characteristic of optimal operation is an appropriate optimising control structure. Evaluating and comparing different candidate controlled variables, an exact characteristic of the optimal operation has not been found. However, some of the candidates are able to maintain optimal conditions with certain accuracy. They are a measure of the temperature symmetry in both parts of the DWC wall, the recoveries of A, B, or C in the prefractionator, and the difference between sidedraw tray and the tray with maximum B composition. Each of them is better than the others facing some disturbances. Thus, depending on the expected disturbances, one or the other will be preferred. The difficulty to measure the different candidate variables is considered. The temperature symmetry variable needs only temperature measures, which is very advantageous.

Simulations show the performance of the MIMO diagonal feedback control strategy consisting in the stabilisation, the composition and the optimising control loops. Tight tuning of the optimisation loop will result in lower boilup values during the composition control transitory. On the other hand, the influence of the optimisation loop on the composition control is relatively small.