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ENERGY OPTIMISATION AND CONTROLLABILITY IN COMPLEX DISTILLATION COLUMNS

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CHAPTER 9. CONCLUSIONS AND DIRECTIONS FOR FUTURE WORK

9.1 Conclusions

The most interesting distillation arrangements for the separation of ternary mixtures reported in the literature are the simple column with sidestream, the conventional column sequences, the columns with side sections, the Divided Wall Column (DWC), and the Petlyuk Column. Basically, these are the arrangements considered in this thesis work. The DWC and the Petlyuk Column, which are thermodynamically equivalent, permit the most reversible processes, due mainly to thermal coupling and a right split of components in the feed tray. For this reason, these distillation arrangements are very attractive in terms of energy and cost savings. In terms of exergy however, these columns are less attractive because they require all the heat at the higher temperature and all the heat removal at the lower temperature.

This thesis work includes synthesis of ternary distillation processes, design of the distillation arrangements, operation, and control analysis. Non-linear and linear dynamic models of the arrangements have been developed for their study. Energy consumption and controllability evaluation has been supported by steady state and dynamic simulations.

Many works, including this one, have contributed to determine the distillation arrangements energetically and economically appropriate for different separation problems. However, the synthesis of multicomponent distillation processes is not solved in a general way. Important simplification assumptions are imposed in most of the works in order to obtain some general trends. But these trends are only useful for primary judgement because real columns behave differently than predicted by simple models. Specifically, in this work it has been seen that results are largely influenced by the assumption of minimum reflux conditions, which does not influence the same way the different arrangements. Studying the influence of the number of trays in the different arrangements, it has been found that the DWC require large columns in order to be energetically advantageous. Therefore, this arrangement is more attractive when the energy cost is high compared to the trays cost.

It seems that synthesis conclusions applying to a wide range of separation problems will be hard to obtain. Instead, the study of specific separations in a rigorous way appears very interesting. From rigorous simulations of different separation examples, the following has been observed:

- For different mixtures and equimolar feeds separated into 0.99 molar purity products at atmospheric pressure, the DWC energy savings are larger for *Ease of Separation Index* close to one.

- For a mixture with *Ease of Separation Index* equal to one and symmetric feeds (A feed composition equal to C feed composition) separated into 0.99 molar purity products at atmospheric pressure, the DWC energy savings are larger when B feed composition is large.

All over the thesis work specific designs have been considered to analyse and compare the different distillation arrangements. Designs that minimise the distillation cost have been given special importance (energy consumption is the main factor in the distillation cost). The design of the DWC is a complex task. DWC design procedures reported in the literature were based on only two decision variables. In this work, a new procedure that uses three decision variables for design optimisation has been proposed. It has been seen that the use of three decision variables is important to avoid excluding possible optimum designs. The method emphasises the importance of having equilibrated separation effort distribution between DWC sections.

In the literature, distillation arrangements for multicomponent mixtures at steady state are in general well described. However, operation and control aspects have been received much less attention. The control of the DWC is more complex than the control of the other distillation arrangements because the DWC has more operation degrees of freedom. In this work, special attention has been given to the DWC control and it has been seen that the DWC complexity offers some design and operation possibilities that permit important controllability improvements. The approach in this work has been to solve the DWC control by levels: the stabilisation, the composition control, and the optimising control.

Different pairs of manipulated variables may be chosen for the first DWC control level, the column stabilisation. The controllability of the stabilised DWC depends on what is this chosen pair. In general, when the manipulated variables for stabilisation control are the distillate (D) and the bottoms flowrate (B), which is the most common stabilisation control structure in the literature, the DWC presents high directionality and interaction. Besides, this stabilisation control structure is not appropriate to the DWC because the DWC has typically high reflux ratios. When the manipulated variables for stabilisation control are the reflux flowrate (L) and the boilup (V), the DWC has better controllability.

Linear analysis tools are useful to select the set of manipulated variables for the DWC composition control. The preferred set of manipulated variables and the controllability of the corresponding control structure depend on the nominal operation.

Controlling the purity of the three products, the DWC has two extra operation degrees of freedom that permit an operation optimisation. This optimisation is used to minimise the boilup. For the DWC stabilised by D and B at optimal operation, the preferred set of manipulated

variables consists in L, V, and the sidestream flowrate (S). This control structure has a high directionality. However, at a non-optimal operation, the preferred set of manipulated variables changes, and the controllability of the new control structure is improved. Therefore, a trade-off appears between operation optimisation and controllability. The set of manipulated variables for the non-optimal operation includes the split of liquid in the top of the wall (*SPLITD*) or the split of vapour in the bottom of the wall (*SPLITB*), what breaks the high directionality of the controlled system.

The preferred set of manipulated variables does not depend on the separated mixture, at least not in an important way, as indicated by results of different examples.

Changes in the design of the DWC can be used to improve its controllability. High directionality is a problem associated to DWC stabilised by D and B that can be improved using a large number of trays. In long columns operated at non-optimal operating conditions, the controllability improvement due to the addition of trays and the controllability improvement due to operation at non-optimal conditions are added. For DWC stabilised by L and V, the use of long columns is also found to improve the controllability. However, in this case, the improvement is less important because even the DWC with a small number of trays has acceptable controllability indexes.

DWC optimal designs have an equilibrated distribution of distillation effort between sections. Non-optimal designs, which break this equilibrium, may also present better controllability, for DWC stabilised by D and B. In this case, the preferred set of manipulated variables for composition control includes *SPLITD* or *SPLITB*, and the directionality of the controlled system is reduced. This indicates a possible trade-off between the design optimality and the controllability of the DWC. As found for operation, also for design, leaving optimal conditions permits to improve the controllability.

Alternatively, for the composition control of the DWC, Dynamic Matrix Control is analysed. It is found that Dynamic Matrix Control performs worse than the diagonal feedback control strategy. It can not afford the control of a DWC stabilised by L and V because the corresponding gain matrix does not exist at steady state. This limitation does not exist for the diagonal feedback control strategy. Also, identification needs to be in the linear area, what makes practically impossible a direct identification from the real process.

Through simulations, it is seen that Dynamic Matrix Control of the DWC stabilised by D and B accuses very much the directionality of the system. This makes the achievement of steady state very slow. In general, tuning parameters of the proportional-integral controllers in feedback control loops have a larger influence on the control performance than the DMC tuning parameters. For disturbance rejection, diagonal feedback control has smaller overshoots. On the other hand, for setpoint changes, Dynamic Matrix Control has smaller deviations.

The two DWC extra operation degrees of freedom can be used dynamically for optimising control. Optimising control objective is to maintain DWC operation close to optimal conditions in spite of disturbances and uncertainty. Due to a marked.directionality found in the response surface, DWC operation may be kept close to optimal operation using only one of the operation degrees of freedom, and fixing the other one at the nominal (optimal) value. Since the control structure with best controllability for the DWC at optimal operation uses L, D, V, B, and S for stabilisation and composition control, the remaining variables for optimising control are $SPLITD$ or $SLPITB$. $SPLITB$ would be very difficult to manipulate. Therefore, $SPLITD$ is the proposed manipulated variable for optimising control.

Optimising control of the DWC through the feedback control of a variable that characterises the optimal operation is possible. Some measurable variables are able to maintain optimal conditions with certain accuracy. However, a measurable variable that characterises perfectly optimal operation is not found. Besides, numerical values show that $SPLITD$ and $SPLITB$ also characterise optimal operation to some extent and therefore, energy losses obtained if they are not used for optimising control are not very large.

The controllability of the different distillation arrangements is compared. Considering at the same time controllability and energy efficiency, it is found that in some cases better controllability and energy savings may be given together. For example, for a specific separation problem, the indirect sequence has lower energy consumption and better controllability than the direct sequence. The same way, the column with side stripper has lower energy consumption and better controllability than the column with side rectifier.

In general, for stabilisation made by distillate and bottoms flowrates, the complexity of a distillation arrangement makes its energy efficiency better but its controllability worse. Therefore, the controllability of the column sequences (with highest energy consumption) is better than the controllability of the column with side sections (with mid energy consumption), and this is better than the controllability of the DWC (with lower energy consumption). However, an important exception has been found. The DWC may give important energy savings as well as the best controllability if it is operated at non-optimal conditions, with SPLITD in the set of manipulated variables.

Also important, when the manipulated variables for stabilisation are internal flows (reflux rates and boilups), the controllability of the DWC is better than the controllability of the other distillation arrangements.

Finally, comparing the controllability of different arrangements for different design conditions, the DWC controllability is found to be more interesting for long columns. Also energy savings of the DWC in base to energy consumption of other arrangements are large when DWC design

consists of long columns. Therefore, the DWC needs long columns to be really attractive in terms of energy as well as in terms of controllability.

To conclude, the DWC permit high energy savings for some separation problems. It also permits good controllability for some specific designs and operating conditions. Moreover, thanks to the arrangement complexity, the DWC may give at the same time energy savings and a the best controllability, what makes it a very attractive distillation arrangement.

9.2 Directions for future work

In general, in the literature as well as in this thesis work, rigorous models have been avoided. Future work should address the analysis of specific examples in a rigorous way. Furthermore, experimental results would be required to validate results and analyse the influence of non-modelled aspects.

Clearly, analysis of new distillation problems will be useful to better determine the appropriate arrangements for different separations. The main lack of knowledge in the synthesis problem addresses separations with low purity of products.

A methodology to tune the DWC feedback loops has not been proposed. Multivariable tuning methods found in the literature do not solve appropriately the tuning of proportional-integral control loops. Better tunings than proposed in this work could improve the performance of DWC control.

Stability analysis of the DWC through rigorous methods such the μ–analysis are required to better compare stability and robustness of the different control structures. The stability analysis could be used for tuning determination.

Finally, the optimisation of the DWC should be mathematically better studied. Multiplicity of solutions could be exploited for operation improvement.