UNIVERSITAT POLITÈCNICA DE CATALUNYA

Department of Chemical Engineering

ENERGY OPTIMISATION AND CONTROLLABILITY IN COMPLEX DISTILLATION COLUMNS

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CHAPTER 1. INTRODUCTION

1.1 Scope

The scope of this thesis work is within multicomponent distillation in continuous processes. Design, operation, and control aspects of different distillation arrangements for the separation of multicomponent non-azeotropic mixtures are studied. However, the core of the work is the study of the non-conventional arrangement Divided Wall Column (DWC).

1.2 Motivation

During the last decades, in the chemical engineering milieu, there has been a growing effort to develop more energy efficient processes. The rising cost of energy and the concern for having a more environmentally sound industry impulse the study of technologies offering energy savings.

Although new separation methods are continuously being explored, distillation remains the most frequently used separation process. Distillation is both, energy intensive and inefficient. It accounts for around 3% of the total world energy consumption and is one of the most energy consuming processes in chemical industry. Reduction of energy consumption in distillation has been actively studied in recent years. Process integration has proven to be very successful in reducing the energy costs for conventional distillation arrangements. However, the scope for integration of conventional distillation columns into an overall process is limited. Practical constraints often prevent integration of distillation columns with the rest of the process. Because of this, attention has been turned to the distillation operation itself. In this sense, heat integrated distillation columns and non-conventional distillation columns have to be considered. Heat integrated distillation columns have been given special attention during the last decades. They consist of conventional distillation columns with energy exchange between some condensers and reboilers. On the other hand, a lot of research effort has been dedicated to non-conventional distillation arrangements.

Following the usual trend in the literature, in this work, the conventional distillation arrangements for multicomponent separations are considered to be the sequences of columns or trains of columns. In the case of ternary separations, for example, there are two conventional arrangements, which are the direct sequence and the indirect sequence of columns. Alternatively, non-conventional arrangements are basically arrangements with a side section or a prefractionator thermally coupled to a main column. They are also known as complex distillation arrangements.

Due to their ability to save energy, complex distillation arrangements have become very attractive. One class of such complex distillation arrangements is the DWC. It is specially energy efficient, but it has rarely been implemented in industry. Industries have been reluctant to use the DWC arguing a lack of knowledge and understanding, and scepticism towards practical issues such as control. However, recent research indicates that these problems may be resolved and motivates to further study this distillation arrangement.

To extend the knowledge of complex distillation arrangements, which permit energy savings, and make them closer to implementation in industry is the motivation of this thesis work. Some design, operation, and control aspects are analysed, having the conventional arrangements as comparison basis.

1.2.1 Design

Distillation bibliography is very vast and multicomponent distillation theory has been studied for decades. The DWC was proposed about fifty years ago (Wright, 1949). Since then, comparisons between the DWC and other conventional and non-conventional distillation arrangements for multicomponent separations have already been published. Petlyuk et al. (1965) studied thermodynamically reversible multicomponent distillation and found that the Petlyuk Column, which is thermodynamically equivalent to the DWC, offered important energy savings. Fidkowski et al. (1986) proposed an optimisation procedure for the thermally coupled system of distillation columns (this was the name they used for the DWC). In a later work, the same authors compared the minimum energy requirement of different complex distillation arrangements and concluded that the DWC had the smallest one (Fidkowski et al., 1987). Other authors have reported energy savings associated to the DWC. Thanks to all these works, it is well known that non-conventional distillation arrangements are more energy efficient than the conventional arrangements for many separations, and differences between arrangements are better understood. However, some design aspects should be further discussed and clarified.

In the same works in what different distillation arrangements are compared, some applications are described. Furthermore, the energy optimality of the different arrangements depending on the separation problem is studied in several works, like those of Tedder (Tedder et al., 1978), Glinos (Glinos et al., 1988), and Agrawal (Agrawal et al., 1998 b) among others. In spite of these publications, the synthesis problem is not completely solved: research effort is still needed to identify the appropriate arrangement, in terms of energy consumption, for any given separation.

Simplifying conditions with important implications are assumed in the literature. Specifically, ideal mixtures and infinite columns (minimum reflux operation) are assumed in the major part of the works where energy requirement of different distillation arrangements is compared. These simplifying conditions may disconnect the analysed synthesis problem from the problem at real conditions because extrapolation of results obtained at extreme operating conditions such as minimum reflux may not be correct. Moreover, the results of some works reveal contradictory conclusions.

Finally, design methods are needed for the complex distillation arrangements, specially, for the DWC. These arrangements present some extra design degrees of freedom, which make the design task more difficult. Trinatafyllou et al. (1992) presented a design model and a design methodology for the DWC. However, it has some limitations that can be overcome.

1.2.2 Operation

Compared to the other conventional and non-conventional distillation arrangements, the DWC has more operation Degrees Of Freedom (DOF). The DOF remaining after the specification of the separation problem requirements may be used for optimisation purposes. In DWC, the optimisation of the operating conditions is important for the achievement of the energy savings. However, not only the determination of optimal operating conditions, but also the sensitivity analysis is important in order to know the difficulty to maintain optimal conditions in spite of model errors and loaded disturbances.

Wolf et al. (1995) concluded that, with four compositions specified, the DWC may display complicated behaviour with multiple solutions and "holes" in the operating range, corresponding to infeasible specifications. With three product specifications, the DWC do not present such problems. With three product specifications, the DWC has two extra operation DOF. They can be used to minimise the energy consumption. Halvorsen et al. (1999) studied the shape of the response surface in the plane of extra DOF.

1.2.3 Control

Within the comparison between different arrangements for multicomponent separations, research effort has been mainly focused in design and steady state operation. Only recently, an article has been published comparing the controllability of three thermally coupled distillation systems (Hernandez et al., 1999). The arrangements considered are the DWC, the column with side rectifier, and the column with side stripper. Conclusions are that the DWC has worse control properties than the column with side rectifier and the column with side stripper. Apart from a previous work (Annakou et al., 1996 b) in what some controllability indexes for the DWC and for a column sequence with heat integration were calculated at steady state, the work of Hernandez et al. (1999) is the first work addressing controllability comparisons between complex distillation arrangements. However, controllability properties are decisive in the process of distillation arrangement selection. In spite of the gotten conclusions, a better knowledge of the controllability properties characteristic of the different distillation arrangements is required. For instance, not the DWC with the best controllability has been considered in the comparison process of the cited work.

Although in an isolate way, control systems for conventional and non-conventional arrangements have been described by some authors, the control of the DWC, the most complex arrangement, and the most promising in terms of energy, has been little studied.

In this decade, some few authors have studied the composition control of the DWC. They have addressed feedback diagonal control strategy. Wolf et al. (1995) proposed some control structures and analysed their controllability. Annakou et al. (1996) calculated at steady state some controllability indexes. Finally, Abdul et al. (1998) suggested that some manipulated variables characteristic of the DWC were maintained constant at their nominal values, and compared two control structures. Literature has thus considered the control of the DWC. However, the extent is quite limited. For instance, none of the works has a systematic comparison between different control structures. The DWC offers more degrees of freedom than the other arrangements and it is very important to explore all possible control structures. On the other hand, only one inventory control structure is considered, and inventory control may have an important influence on the composition control. Any author neither considers the dependence of the DWC controllability on nominal operating conditions and design.

For good controllability, it is very important to consider the appropriate design (Luyben, 1990). For simple distillation columns, Skogestad (1997) discussed the effect on the controllability of adding distillation stages. However, for complex distillation arrangements, no analysis of this kind has been performed.

In the literature, control strategies different from the feedback diagonal control for the DWC have not been presented. However, conventional consensus is that Model Predictive Control (MPC) is typically best suited to Multiple Input Multiple Output (MIMO) processes with significant interactions between Single Input Single Output (SISO) loops, and to processes with complex and unusual problematic dynamics such as long time delays, inverse response, or unusually large time constants (Ogunnaike et al., 1994). Also, Dynamic Matrix Control (DMC) has proven superior in distillation control when faced either with constraints or for controlling more than two compositions (Luyben, 1992). Therefore, the DWC is a good candidate for DMC application because it has

MIMO variables with significant interactions between SISO loops, inverse response, large time constants, and three products the composition of which should be controlled.

1.3 Objectives

As a consequence of what has been explained in the previous section, the main objective of this thesis work is to extend the scope of the knowledge of non-conventional distillation arrangements properties in design, operation, and control fields, in comparison with the properties of the conventional distillation arrangements. Taking all these aspects into account, this work pretends to be a help for determining which distillation arrangement is more convenient for a given separation process. In design, to define optimality regions of the different distillation arrangements, and to describe good design methods for the DWC are the main objectives. In operation, study of optimal operating conditions of the DWC is the main objective. In control, the search of the best control strategy for the DWC, the analysis of DWC operating conditions influence on the controllability, the analysis of DWC design influence on the controllability, and the comparison of the controllability of different conventional and non-conventional distillation arrangements are the main issues.

With its complex structure, the DWC is often the most advantageous arrangement in terms of energy. But precisely its complexity makes the engineers feel less confident with it. Because of that, the exploration of all possibilities offered by the DWC complexity has been a specific objective of the thesis.

1.4 Organisation of the thesis work

To develop the objectives enunciated in the previous section, the thesis work has been distributed into seven chapters (plus introduction and conclusions), covering the following aspects:

In chapter two "Different distillation arrangements for multicomponent separations", there is a general overview of the principal distillation arrangements for multicomponent separations proposed in the literature. For all them, detailed descriptions referenced during the thesis work are given. Non-conventional and conventional arrangements are all compared from a theoretical point of view, at steady state conditions. A special attention is given to reversibility and thermal coupling, thermodynamic properties that only the DWC has at the same time, which make the DWC highly energy efficient. Design procedures and operation DOF used all over the thesis are also described in this chapter. Specially, for the DWC, design methods described in the literature are discussed and limitations identified. To overcome these limitations, a new design heuristic is proposed, which will be useful for the posterior chapters.

In chapter three "Appropriate arrangements for different separations", which are the appropriate distillation arrangements for different separation problems is studied. The parameters considered are energy consumption and total distillation cost. A compilation of the results found in the literature is done and conciliation between conclusions of different works is analysed. The effect of the assumed simplifying conditions on the conclusions of these works is analysed. Through rigorous simulations, a contribution to the definition of the optimality region for the DWC is done, and some applications are described. Since the use of complex distillation arrangements, specially the DWC, is motivated by its ability to save energy, some of the favourable applications described will serve as case studies in operation and control analysis in posterior chapters.

Chapters four to seven are dedicated to the control of the DWC. A non-linear model of the DWC, appropriate for the control study, is developed. It is described in chapter four "MIMO feedback control analysis of the Divided Wall Column". From the non-linear model, a linear model is derived, which will be useful for control linear analysis tools. Both models are used in all control chapters of the thesis. In chapter four, DWC composition control through decentralised feedback control is studied. All the possible control structures offered by the DWC complexity are considered and compared in order to identify the best ones. Importance has been given to the inventory control structure. With the same objective of exploring all possibilities of a better controllability, the effect of the operation optimisation (energy minimisation) on the DWC controllability is studied. Since the DWC studied applications present high non-linearity, in order to diminish it, the logarithms of compositions as output controlled variables (instead of the compositions themselves) are studied. Tuning methods have been discussed and simulations performed.

In chapter five "Dynamic Matrix Control applied to the Divided Wall Column", the application of DMC to the DWC is studied. Through simulation, this control strategy is compared to the decentralised feedback control strategy implemented with PI controllers. Specifically, ability for disturbance rejection and set point tracking of the two strategies is compared.

Chapters four and five only address composition control. Since the DWC has some extra DOF that can be used for optimisation, in chapter six "Optimising control in the Divided Wall Column", optimising control of the DWC is studied. First of all, a sensitivity analysis is done in order to evaluate the optimising control necessity. Then, how to dynamically maintain the operation of the DWC at the minimum energy operating conditions, using the extra DOF, when disturbances are present or setpoint changes are required is studied. Feedback control of some variable characteristic of the optimal operation has been considered for the optimising control and different candidate variables are quantitatively compared through optimisation and rigorous simulation.

The controllability of the DWC depending on design is studied in chapter seven "Controllability of the Divided Wall Column depending on design". Optimal and non-optimal DWC designs are considered. The relation between controllability and design optimality is analysed, as well as the effect on the controllability of adding distillation stages. Based on the optimal design, separation effort is transferred from one section to another by removing and adding stages to different sections. This way, different designs are obtained, the control properties of which are analysed and compared.

Finally, in chapter eight "Controllability of different distillation arrangements", the controllability of different distillation arrangements is compared. Control structure and nominal operating conditions selected for the best controllability of the DWC are considered. Different designs of all the arrangements are also considered. The controllability comparison is developed in parallel to the energy efficiency comparison, in order to analyse both properties at the same time.

1.5 Contribution

Considering the thesis work as a whole, it is a contribution to the comparison between different distillation arrangements for the separation of mulicomponent mixtures, with a deep analysis of the DWC.

The thesis work provides a better knowledge of the advantages and disadvantages of the different distillation arrangements. Energy requirement and controllability are the most emphasised properties. Conventional and non-conventional arrangements are studied with the objective of knowing whether or not and when energy minimisation and satisfactory control can be given together.

The more complex of the non-conventional arrangements is the DWC. Since the DWC is very attractive from an energy point of view and its complexity makes it a rare process, the study of its properties has become a principal contribution of the thesis work.