Chapter 1

INTRODUCTION

1.1 Motivation

Increased energy cost, increased focus on environmental aspects and generally harder competition have all contributed to increasing demands regarding efficiency within the process industry during the last decades. Higher efficiency is often obtained through designs with increased process integration. Simple examples of process integration are separation and recycling of unreacted feed in the outlet stream from a reactor (material recycle), or utilizing the excess heat in a hot outlet stream from an exothermic reactor to preheat the feed using a heat exchanger (energy recycle). An efficient overall solution can usually not be achieved from one single recirculation, and tight and plantwide process integration is often required. For instance, all hot process streams may be integrated with all cold process streams in a heat exchanger network. In addition to this heat integration, there may be a number of material recycles together with integration of turbines, heat pumps etc.

Process integration is motivated from economic benefits, but it also changes the characteristics of the plant: Instead of addressing each process unit independently, the total plant has to be investigated as a whole (a systems approach). This issue should be particularly emphasized when considering *operation* and *control* of the plant, mainly due to the two following points:

1. Process integration increases interactions in the plant. That is, a change in a disturbance or manipulated input may not only give local effects, but can spread to a larger part of the plant.
2. Process integration may dramatically change the plant dynamics. As a severe example, integration of units that are all stable may result in an unstable plant.

In addition, process integration often introduces extra degrees of freedom that may be utilized for optimization during operation. This may be thought of as a possibility for further savings, but usually the situation is exactly the opposite: A process design is based on the assumption that the process is operated optimally without disturbances, and therefore the extra degrees of freedom may have to be used for optimization during operation in order not to deteriorate the benefits that process integration can give.

For the reasons pointed out above, it is clear that operation of integrated processes can be both difficult and important for the total economy of the plant. This gives motivation for further research within these two areas:

1. Design of integrated processes which also are easy to operate/control.
2. Design of operation/control systems for integrated processes.

Both of these areas are challenging and they are somewhat related to each other. Despite that the first point in some cases may be a prerequisite for obtaining good results in the second point, this thesis focuses on design of systems for operation and control of integrated processes.

In many plants, energy costs constitute a significant fraction of the total operating costs, and methods for optimal operation of heat exchanger networks (HENs) are particularly emphasized in this thesis.

1.2 Scope and overview of thesis

The main goal of this work is to contribute within the field of optimal operation of HENs. Mathisen (1994) formulated this problem as follows:

"For a HEN with given structure, heat exchanger areas and bypasses, and a given steady-state operating point (supply temperatures, heat capacity flowrates, heat transfer coefficients and target temperatures), find the set of manipulated inputs (bypass fractions and possible split fractions) that minimizes energy cost."

In addition to minimization of energy cost, it is also important to have a strategy for operation and control that results in reasonable dynamic performance of the plant. In general, we want a control system that yields a stable plant that rejects disturbances and follows setpoint commands fast and smoothly. Methods that minimize energy cost during operation together with reasonable plant dynamics are proposed in the thesis. Where it is possible, it has been attempted to generalize the methods to be applicable for other parts of processes than HENs.

The thesis consists of a total of eight chapters which are written to form one entirety. Despite this, some of the chapters can be read independently of the others as long as chapter 2 has been read. In order to succeed in proposing good methods for optimal operation of HENs, it is required with some basic knowledge both from the field of process synthesis and from the field of process control. This knowledge, together with some basic ideas on how to approach the optimal operation problem is given in chapter 2. In order to verify that the proposed

methods work, dynamic simulations are made and chapter 3 presents how this is done for HENs.

In order to perform optimization during operation, it is required that there are extra degrees of freedom after regulatory control is implemented. This is discussed in chapter 4, and it is shown that degrees of freedom may not always be utilized for energy optimization. A quantitive expression for the degrees of freedom that can be used for optimization is presented together with some simplified rules.

Chapter 5 discusses a method for optimal operation that is based only on the structure of the HEN. This method is presented earlier, but in this chapter parallels are drawn to split-range control. A way to deal with multiple controlled temperatures is also proposed. A method which is heavily inspired by this socalled sign method is presented in chapter 6. Here, quantitative information in terms of linear steady state transfer functions is utilized, and a control configuration that minimizes energy cost is found by solving an integer programming problem.

A different approach for optimal operation of HENs is proposed in chapter 7. This chapter actually contains two methods that are combined to form one powerful strategy for on-line optimization. A general steady state HEN model is formulated which is used periodically during operation to find optimal setpoints for a set of variables. In addition, a method for selection of *which* variables that are kept at setpoints between the optimizations is proposed. Special attention is paid to processes where optimum lies at the intersection of constraints, which is typical for HENs.

The last chapter provides a short discussion in addition to conclusions and suggestions for future work.

Each chapter has a separate nomenclature and reference list at the end. Earlier and more "stand-alone" versions of chapters 5 and 7 have been presented at ESCAPE-6 on Rhodes, Greece in May 1996 and at PSE-ESCAPE'97 in Trondheim, Norway in May 1997, respectively. These chapters have been partly rewritten; some topics have been more emphasized and some new parts have been included. Also, some introductory issues have been removed as these now are presented more thoroughly in chapter 2.

1.3 Related work

Synthesis of HENs is a mature research field and Gundersen and Næss (1988) cite almost 200 papers in their review article. The two dominating synthesis methods have been the pinch design method and mathematical programming. Gundersen *et al.* (1991) show that both of these methods may fail to find the global optimal solution. Further development still takes place within HEN synthesis, including methods that combine elements from different approaches.

Compared to the large literature on HEN synthesis, the number of publications concerning operation of HENs is much less. A prerequisite for optimal operation is that the HEN is sufficiently flexible (i.e. feasible operation for variations/disturbances that may be

encountered). Kotjabasakis and Linnhoff (1986) introduced sensitivity tables in order to make a base case design flexible, and a later contribution by Papalexandri and Pistikopoulos (1994a) introduces a model that includes flexibility requirements in the synthesis stage using a mathematical programming approach.

Control of single heat exchangers is considered several places in the literature, see e.g. Shinskey (1988). For regulatory control of complete HENs, Nisenfeld (1973) used the steady state RGA to find the pairing between measurements and manipulations. Mathisen *et al.* (1992) discusses controllability and control structure selection for HENs, however, energy consumption is not considered. An important contribution to controllability and control structure design in HENs is given by Mathisen (1994, chapters 3 and 4). That contribution also comprises aspects related to energy consumption, and it constitutes an important basis for a large part of this thesis.

Design of operable HENs is discussed by Marselle *et al.* (1982) and heuristic rules are proposed in order to guide the designer to find a base case HEN structure with the most promising properties concerning operability (flexibility and controllability). Mathisen (1994, chapter 7) proposes rules for use together with the pinch design method to achieve HENs with good operability properties. Operability considerations in HEN synthesis using mathematical programming is discussed by Mathisen (1994, chapter 8) and linear constraints that include operability aspects are added to Yee's stagewise model for HEN synthesis (Yee and Grossmann, 1990). A different approach for incorporation of controllability into HEN synthesis is proposed by Huang and Fan (1992) where a knowledge based strategy is proposed. Papalexandri and Pistikopoulos (1994b) include dynamics and control structure considerations in the synthesis stage using a mathematical programming approach.

Even if there is a growing literature that aims to incorporate operability aspects in the synthesis stage (research area 1 on page 2), few publications have been devoted to methods for operation of HENs (research area 2 on page 2). Marselle *et al.* (1982) and Calandranis and Stephanopoulos (1988) suggest to manipulate the duty of the last heat exchanger on a stream, however, this may not be preferred from an energy consumption point of view. Methods for operation of HENs should not only include regulatory control (keep outlet temperatures at targets), optimization should be regarded as well. That is, the method should automatically find the *optimal* operating state when the are variations in disturbances, target temperatures or in the process itself. Mathisen (1994, chapter 5) suggests a method for optimal operation of HENs that utilizes structural information. The method comprises energy optimization in addition to regulatory control, and chapter 5 in this thesis is based on that method. Bojaci *et al.* (1996) proposes a method for operation of HENs that is based on repeated steady state optimization, but their focus is not on the closed loop control system.

Recent work on control structure design by Skogestad and coworkers involves selection of controlled outputs for optimizing control, see Skogestad (1996, chapter 10) and Morud (1995, chapter 8). This may be utilized for optimal operation of HENs and it is incorporated in the method proposed in chapter 7 of this thesis.

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