Chapter 8

DISCUSSION AND CONCLUSIONS

In this concluding chapter, the first section provides a short discussion focusing on the compliance with industrial HEN operation problems. The second section summarizes the conclusions and contributions of the thesis. In the third and last section, some suggestions for future work within the area of operation of HENs are given.

8.1 Short discussion

This section provides a short discussion of some of the main topics covered in the previous chapters. The emphasis is on compliance with industrial problems.

In this thesis, the HEN operation problem has been treated to be completely decomposed from other parts of the process. This is in accordance with most other academic work within this area. In section 2.1 it was argued that "good" control of the HEN is desired as it gives "small" interactions and "small" effects of unwanted feedback in the overall plant. Thus, good control of the HEN (treated as a separate system) is important for the overall plant behavior. For the *industrial* HEN operation problem, a number of deviations from common assumptions may be faced. Examples are:

1. Heat capacity flowrates are often assumed to be constant, or changes in heat capacity flowrates are treated as *disturbances*. In practice, there are cases where flowrates actually are *manipulations*.
2. For an industrial HEN operation problem, temperatures *internally* in the HEN may have (soft) targets. As an example, consider a steam generation plant where an economizer is placed before the boiler. The outlet temperature from the economizer will have an upper limit to prevent boiling in this unit.

3. In this thesis, it is assumed that utility exchangers (where present) always are located as the last unit on the stream. For the industrial HEN operation problem, there may exist internal utility exchangers, for example when multiple utilities such as various steam levels are present.
4. In operability and flexibility analyses, it is often assumed that *all* heat exchanger duties can be manipulated through a bypass. This is only rarely the case for industrial HENs.

Now, some short comments to these 4 points related to the previous chapters are given. The three different methods for operation of HENs presented in the preceding chapters can deal with the first point (flowrates as manipulations) without any particular difficulties. The four observations in chapter 5 give the necessary information for putting up sign matrices when flowrates are used as manipulations. For the methods in the chapters 6 and 7, a flowrate manipulation is treated as any other manipulation. When using flowrates for manipulations, one should keep in mind the non-convexity problem that may be encountered. Chapter 4 concerning degrees of freedom during operation does not, however, consider using flowrates as manipulations.

The second point concerning internal temperature targets has not been treated explicitly in the thesis. If there is a target temperature between two heat exchangers in a HEN, one option is simply do redraw the HEN such the stream with internal target temperature is defined as two separate streams. This does not apply for targets within a bypass line. While internal targets are not explicitly considered, an internal measurement does not differ from any other measurement/output. Internal targets are discussed in Mathisen (1994, p.115). Regarding DOF during operation, an internal target represents an additional constraint in the inner HEN. When computing $N_{\mathrm{DOF,\,U}}$, this *may* reduce the rank of the inner HEN and thus reduce the number of DOF.

The third point concerns internal utility exchangers. If the duty of an internal utility exchanger is used for control of the temperature immediately downstream, then one should definitely consider redrawing the HEN such that the stream with an internal utility exchanger is treated like two separate streams. If the duty of an internal utility exchanger cannot be manipulated, it will not pose any difficulties. For a internal utility exchanger controlling some other temperature than immediately downstream, that manipulation can in principle be considered as any other manipulation. Computing DOF during operation, an inner utility exchanger is part of the inner HEN. Thus, the inner utility exchanger may affect the rank of the inner HEN. Further, inner utility exchangers are not considered for the general structure of HENs described in section 2.3 (page 21).

The fourth and last item above points out that a common assumption for flexibility and operability analyses (at least in academia) is that *each* heat exchanger has a bypass. While this assumption may have been used for illustration purposes early in the chapters concerning operation (chapters 5, 6 and 7), all of the methods described handle heat exchangers without bypasses. Chapter 4 concerning DOFs in operation also covers heat exchangers without bypasses. In chapter 2, the *effective* flexibility is introduced in order to point out that it is the flexibility of the *controlled* HEN that matters during operation

In addition to these 4 points, one may face other and more problem specific challenges for the industrial HEN operation problem. These may be related to fouling, interaction between heat and material balances, thermal energy versus mechanical/electrical energy etc.

The industry has for a long time been concerned about energy consumption and how to operate the plants in order to maximize heat recovery. While there exists fairly general and simple methods for *design* of energy efficient plants (e.g. the pinch design method), strategies for *operation* of HENs have often been developed in a much more *ad hoc* manner. For instance, the strategy for operation may be based on experience from similar plants, or from simulations of one or a few selected control strategies. In many cases, such approaches will result in good control strategies for the particular plant. The purpose of the work presented in this thesis, is to equip personnel involved in operation of plants (or design of control strategies) with *systematic* methods that result in equally good (or better) control strategies in a faster and more reliable way.

One may ask why not use some general optimizing control scheme such as Model Predictive Control (MPC) for operation of HENs. MPC has experienced a growing popularity in industry during the last years and the number of implementations is increasing (Morari and Lee, 1997). In industry, MPC is usually implemented on top of the regulatory control system. One reason for not using MPC for the control of HENs is, as it has been shown in the thesis, that many HENs can be operated optimally using traditional decentralized control. Simple physical insight and using e.g. the sign method in chapter 5, will in many cases lead to which bypasses that should be opened and which should be closed in order to achieve optimal operation. This is a much simpler method than MPC, and should therefore be preferred. MPC requires a dynamic model of the process to be operated, while the 3 methods presented in the thesis all have less requirements concerning the process model.

An important difference between the 3 presented methods is the amount of information needed. For the sign method in chapter 5, only the *structure* of the HEN is used to deduce how it should be operated. In cases where structural information alone is not sufficient, the parametric method described in chapter 6 may be an alternative. This method is very similar to the sign method, except that the signs are replaced by numbers. However, no information about the disturbances is required. Chapter 7 describes the third method for operation of HENs, and this method differs significantly from the other two. Among the 3 methods, this last method requires most information about the HEN. It uses a complete steady state model and in addition information about disturbances is utilized. Which method to use may depend on the available information.

Finally in this section, it is emphasized that there are cases where the HEN can be designed to operate optimally with zero degrees of freedom. As an example, consider a HEN with 1 DOF when all process exchangers have bypass. If it is found (e.g. from simulations) that one of the bypasses should always be closed (i.e. keeping this bypass closed minimizes utility cost for all operating regions), then this bypass should not be installed. In such cases, the HEN is always operated optimally in a trivial manner. This thesis has focused on cases where there is at least 1 DOF, and where there is a need for a strategy during operation in order to minimize the energy consumption.

8.2 Conclusions

This section summarizes the main conclusions and contributions in this thesis.

In chapter 2, it is argued that the HEN can be considered as a separate part of the process, with its own properties regarding heat recovery level and dynamic behavior. The most important aspect of operation of HENs is to maximize heat recovery, however, good dynamic properties also reduce the influence of undesired feedback in the overall process introduced by heat integration. While it is rather obvious that the process structure affects the operability, chapter 2 also points out that the opposite sometimes may be the case. If e.g. the control system applies a bypass fraction of 1, this corresponds to removing the bypassed unit.

Chapter 3 concerns dynamic simulation of HENs. While this chapter does not contribute significantly, it gives some recommendations regarding how to model HENs to obtain simple dynamic simulations. The chapter concludes that modeling each side (hot and cold) of a heat exchanger as a series of tanks and using arithmetic mean as the temperature driving force (AMTD), in most cases gives good agreement with steady state properties combined with fair dynamic behavior. This result is found through two different approaches (modifying the pure mixing tank concept, and discretizing one-dimensional partial differential equations).

The perhaps most important contribution in this thesis is chapter 4. This chapter shows that all degrees of freedom (after control of targets is implemented) may *not* be utilized for energy optimization. The number of DOFs that *can* be utilized for optimization of utility cost ($N_{\mathrm{DOF,\,U}}$) is defined, and a novel quantitative expression for $N_{\mathrm{DOF,\,U}}$ is derived. An important step in developing this expression is to divide the HEN in one inner and one outer network. A bottleneck to $N_{\mathrm{DOF,\,U}}$ is often the number of process streams entering the outer HEN, thus increasing the number of manipulations (bypasses) in the inner HEN may not always increase $N_{\mathrm{DOF,\,U}}$.

Relaxing one target temperature to become a free outlet temperature increases $N_{\mathrm{DOF,\,U}}$ by one. A surprising result in chapter 4 is that relaxing another target temperature does not increase $N_{\mathrm{DOF,\,U}}$ any further. In addition to the quantitative expression for $N_{\mathrm{DOF,\,U}}$, a simple rule to determine whether optimization may be possible or not is presented. It is also shown that the quantitative expression may be simplified considerably by assuming that the rank of the inner HEN is only limited by the number of process streams and the energy balance.

In chapter 5 it is shown that how to operate a HEN optimally may often be deduced from structural information only. This “sign” method for optimal operation of HENs has been presented earlier by Mathisen (1994, chapter 5). However, chapter 5 in this thesis includes some further development of the method. First, the definition of the signs has been redefined to fit a general process and not only HENs (previously, the definition of the signs depended on whether the corresponding stream was hot or cold). This improvement makes the method applicable to all types of processes with at least one extra DOF for optimization and where information about the signs is available. It is emphasized, however, that the sign method does not always guarantee optimality. Second, the presentation of the procedure is simplified with the introduction of the vector g^{U} denoting the effect of each manipulation on the *total* utility consumption. This does not change the method itself, but is included to make the procedure simpler to understand and to make it more similar to the parametric method. The sign

method results in a priority table denoting the preferred manipulation, and which manipulation to switch to if the preferred manipulation is saturated. Chapter 5 shows that this variable control structure in some cases simply is identical to split-range control.

The parametric method in chapter 6 is very similar to the sign method. In fact, replacing the signs in the sign matrices with real numbers is the most important difference. The control structure that optimizes the utility consumption is found by solving an integer programming problem. Note that if there is only one bypass controlled temperature, this optimization is reduced to selecting the smallest number from a vector (similar to the priority table of the sign method). For HENs with multiple bypass controlled temperatures, the method does not guarantee that the optimal solution is found. The basic optimization model does not include any controllability considerations and the basic model is extended to include controllability in two different ways. Controllability is included by additional constraints which in both cases represent a hierarchical control strategy. It is shown that these hierarchical strategies can be implemented by logical propositions formulated as additional mathematical constraints involving binary variables. In this way, logic inference is embedded into the optimization model. It is not external logic in terms of "if-then" statements etc. added on top of the basic formulation.

Chapter 7 presents a different approach to optimal operation of HENs. This method combines periodic steady state optimization and optimal selection of secondary measurements. While periodic steady state optimization does not represent much new, a general model designed for optimization of HENs is presented. The basis of the method for selection of measurements is also presented earlier (Skogestad and Postlethwaite, 1996, chapter 10). The contribution in the thesis is to adapt and apply the method for processes where optimum lies at the intersection of constraints. This is often the situation also for other parts of a process than the HEN. The problem in such cases is that the nominal optimum may be infeasible when unknown disturbances or model errors are present. Therefore, the selection of measurements have to be based on values that are optimal when unknown disturbances and model errors are considered. A second, but related problem is to find the optimal value of the selected measurements considering unknown disturbances and model errors (robust optimum) during operation. In order to avoid computing optimal values for all possible disturbances periodically, it is proposed to use an additional constraint (safety margin) that represents the difference between the nominal and the robust optimum. This constraint is computed once and by adding this constraint to the model, estimates for the robust optimal values will be found directly, i.e. without considering all possible unknown disturbances and model errors. It is shown that the robust optimal values are different from the nominal optimal values also for systems with asymmetric objective functions. An asymmetric objective may occur when deviations in the primary variable are penalized rather than considered infeasible. Also in such cases, a safety margin can be used to find robust optimum directly.

8.3 Suggestions for future work

This thesis is devoted to operation of integrated processes, and in particular to operation of HENs. Even though this may seem to be a well defined and perhaps also a narrow research area, there is definitely room for further work. This section suggests some directions for

future work related to the main parts of the thesis. The topics are not prioritized, and they appear in the same order as they do in the thesis.

Simple dynamic simulation of HENs can be performed using the models described in chapter 3. One possibility is to further investigate the limitations imposed by the use of AMTD, and to find conditions at which the use of AMTD leads to crossover at steady state. Also, for more accurate dynamic predictions, more detailed models are required. This may include modeling of heat exchangers where the fluids are compressible and heat exchangers where phase transitions take place. Further, models that more explicitly include the mechanical construction of the unit may be needed.

Even if degrees of freedom for optimization during operation of HENs are given a fairly thorough treatment, future work could be to include the use of flowrates as manipulations. It may be argued that this is implicitly included in chapter 4 since it will affect the rank of the inner HEN. With flowrates as manipulations, it may be expected that the energy balance is not constraining the rank of the inner HEN. A consequence of this may be that relaxing a target to a free outlet temperature will not increase $N_{\mathrm{DUF,\,U}}$. Such issues should be addressed in future work.

Regarding the sign method for optimal operation of HENs, more work can be done in order to find classes of HENs for which optimal operation is guaranteed. Also, more work is needed for HENs with more than one bypass controlled target. A method to handle multiple bypass controlled targets is presented in the thesis, however, this method should be verified on larger examples, and alternative solutions should also be assessed.

The sign method as it is presented in chapter 5 is not restricted only to HENs. The method can be regarded as a general framework for utilization of structural information in operation. Future work should include application of the method on other types of processes. The method is, however, not assumed to be well suited for processes where optimum is unconstrained.

The parametric method in chapter 6 is basically the presentation of an idea, and further work is needed to develop it into a method that can be recommended in practice. This will have to include investigating under what conditions the method may fail to reach the optimal operating state. How to incorporate controllability considerations could also be further developed in addition to the 2 methods proposed in chapter 6. The way logical constraints are used to obtain hierarchical control strategies, could perhaps be utilized in other optimizing control schemes such as MPC. In section 6.7 it is argued that the method has a potential of being robust to model errors and this should be further investigated. As for the sign method, examples from other processes than HENs should be studied in order to verify and further develop the parametric method.

The method combining steady state optimization and selection of secondary measurements in chapter 7 is at a level where it can be applied in practice. Of course, a practical implementation has to handle problems like, “what if the optimizer does not return a feasible solution?” or “how much should setpoints be allowed to change from one optimization to another?” etc. Future work on this method should include larger examples (more than one secondary manipulations) and the effect of having a constant value for the safety margin should also be investigated.

References

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