STRATEGIES FOR THE OPERATION AND CONTROL OF HEAT EXCHANGER NETWORKS

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Abstract

The continued high cost of energy has mandated that the Chemical Process Industries reduce operational and capital costs through process heat integration. However, the heat integration of process streams can lead to process structures that are difficult to operate and control. This paper addresses the control of heat exchanger networks and it shows the importance of dynamic simulations in the synthesis of workable control structures. Steady-state simulations were used to delineate the trade-off between flexibility and capital costs of networks. Dynamic simulations were used to assess the placement of the by-pass on the process-to-process heat exchangers. Steady-state simulations showed that the use of stream splitting should be avoided as a control scheme. For control purposes the methodology of Glemmstad and Gundersen's (1998) was modified and improved upon in order to determine the degrees of freedom of a heat exchanger network. Heuristic rules were proposed to identify the best control strategy for a heat exchanger network.

Keywords

Heat Exchanger Networks, Degrees of Freedom Analysis, Control Strategy Determination.

Introduction

Heat exchanger networks (HENs) are widely employed in the chemical processing industries to recover energy, resulting in reduced capital and operating costs. However, the heat integration of process streams can lead to process structures that are difficult to control. Process control of individual heat exchangers is well understood, however the process control of HENs is still an immature subject. Luyben et al (1997) present a general procedure for plantwide control, where it is emphasized that energy integration profoundly alters the dynamic behavior of the plant and therefore special attention must be paid to process-to-process heat exchangers. Mathisen et al. (1992) present some specific rules for bypass selection for control of HENs. Glemmestad and Gundersen (1998) developed a degrees of freedom analysis that can be used to check if the operation of HENs can be "optimized". This optimization procedure is described in more detail by Glemmestad et al. (1997). However, it is possible to achieve better operation using some simple control structures. This paper critically examines the schemes employed to control heat exchangers and HENs. Then a degrees of freedom analysis for process control is presented. Finally, a set of heuristic rules for process control of HENs is proposed.

Control strategies

The most common strategies for the control of outlet temperatures in a HEN are via bypass flow of process-to-process heat exchangers, duties of process-to-utility heat exchangers (utility streams flow rates) and flow rate

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division via process stream splitters. Each of these strategies was analyzed with the aim of proposing a set of heuristic rules for the synthesis of control structures for HENs.

Process-to-utility heat exchangers

A hot process stream may be cooled down using a cold utility such as cold water. In the same way, a cold process stream may be heated up using a hot utility such as low-pressure steam. Several different control schemes can be used to control the outlet temperature of the process stream, such as throttling the utility fluid, throttling the process fluid, and bypassing the process fluid (e.g. Svrcek et al., 2000 and Driedger, 1998).

Process-to-process heat exchangers

A bypass stream is usually employed to control the outlet temperature of one process stream in a process-to-process heat exchanger, as shown in Figure 1.

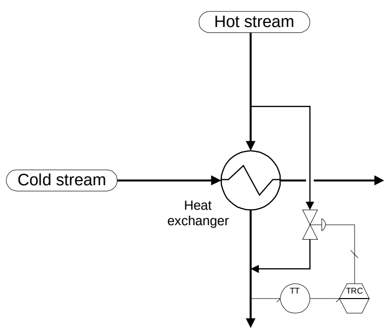


Figure 1. Process-to-process heat exchanger

It can be seen that only one outlet temperature can be controlled in a process-to-process heat exchanger. The action of the bypass stream can be explained as follows: if for any reason, the outlet temperature of the hot stream is greater than its setpoint, the flowrate through the bypass stream must be decreased, because this action will cause an increase in the heat exchanger's duty (direct acting controller). In order to deal with positive and negative disturbances, the heat exchanger has to be designed with a steady-state flow rate for the by-pass stream different than zero. Steady-state simulations were developed using HYSYS where the trade-offs between flexibility and capital costs were examined. Figure 2 shows the typical behavior of the maximum inlet disturbance as a function of the nominal by-pass flow fraction. The maximum inlet disturbance is defined as the maximum or minimum values relative to the steady-state operation that an input variable (inlet temperatures or flow rates) can be changed by and the controller can still keep the outlet temperature under control. In order to develop more realistic simulations, the bypass flowrates were varied from zero (closed valve) to two times the nominal value (fully open valve).

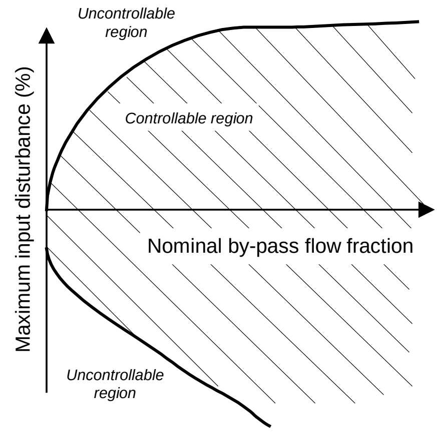


Figure 2. Flexibility versus nominal by-pass flow fraction

It is obvious from Figure 2 that a more flexible operation can be attained if the heat exchanger is designed with a large nominal by-pass flow fraction. Figure 3, however, exemplifies the impact of a bypass stream (20% flow fraction) on the temperatures of a heat exchanger.

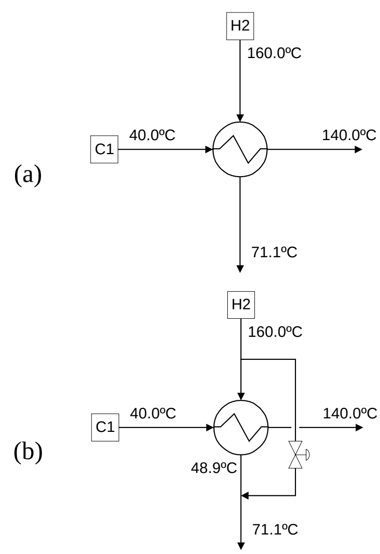
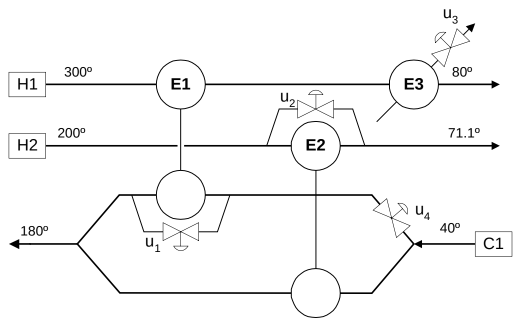


Figure 3. Influence of by-pass stream on temperatures

The temperature differences in the heat exchanger shown in Figure 3b are smaller than in Figure 3a. As a consequence, the area and the cost of a heat exchanger designed with a bypass stream is greater than one with no by-pass. Moreover, the number of shells in series usually has to be increased in order to avoid infeasible designs of 1-2 shell and tube exchangers. It is concluded that there is a trade-off between controllability and capital costs in process-to-process heat exchangers.

Another question to be addressed is the correct placement of the bypass stream (on cold or hot side of the heat exchanger). In the case studies developed in this research project, steady-state simulations suggested that more flexibility is obtained with less capital cost when the by-pass stream is placed on the stream with larger heat flowrate capacity. However, dynamic simulations showed that a better control performance is attained when the bypass stream is placed on the same side of the heat exchanger where the outlet process stream temperature is controlled.

Stream splitters



E1, **E2** and **E3**: proces-to-process heat exchangers

Figure 4. Network with stream splitting

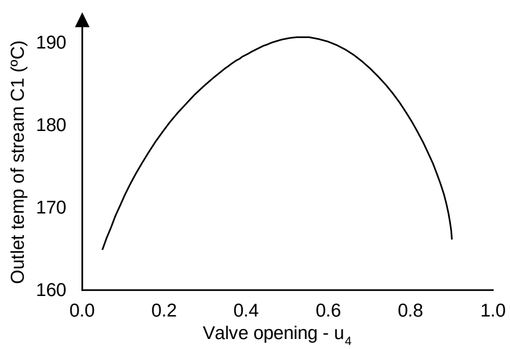


Figure 5. Influence of flow rate division on outlet temperature

Some authors (e.g. Oliveira et al., 2001) suggest that some outlet temperatures in a HEN could be controlled by manipulating the flowrate division in stream splitters. Steady-state simulations were developed for the network shown in Figure 4, and the influence of the flow rate division (u_4 valve opening) on the outlet temperature of stream C1 can be seen in Figure 5. The shape of the curve plotted in Figure 5 suggests that flowrate division in a stream splitter should not be used as a manipulated variable, because the controlled variable must be a monotonic function of the manipulated variable, otherwise no control law can be derived. Moreover, the Relative Gain Array (RGA) (e.g. Svrcek et al., 2000) was used to compare control strategies, and for the specific example shown in Figure 4, the use of variables u_1, u_2, and u_3 results in a better control performance than any strategy using u_4. In conclusion, the flow division in a stream splitter should never be used as a manipulated variable for process control.

Degrees of freedom analysis

The methodology developed by Glemmestad and Gundersen (1998) was adapted to check if a network can be controlled. From a process control perspective, the number of degrees of freedom is calculated as the number of possible manipulated variables minus the number of controlled variables. If the number of degrees of freedom is positive, it means that there are more manipulated variables than necessary and the process can be controlled. However if it is negative, there are not enough manipulated variables to be paired with all the controlled variables, and therefore, the process cannot be controlled. In the case where the number of degrees of freedom is equal to zero, there are just enough manipulated variables and the process can be controlled. In the context of HENs, the candidates for manipulated variables are duties of process-to-utility heat exchangers (for example: by means of throttling the utility flow rate) and duties of process-to-process heat exchangers (by means of manipulating the bypass flow rate). So the number of candidate variables for process control is equal to the number of heat exchangers. The number of controlled variables is equal to the number of outlet temperatures that must be controlled.

However, loops add constraints for process control. For the network shown in Figure 6, although there are 2 heat exchangers, their duties are dependent and so there is only 1 independent manipulated variable. Figure 7 shows a network with a more complicated loop. Process simulations were developed using HYSYS and the RGA was calculated. From the RGA, it can be concluded that it is not possible to pair all outlet temperatures with all by-pass flow rates. Moreover, the Niederlinski Index (e.g. Svrcek et al., 2000) was calculated and it showed that the process is unstable. This conclusion can be reached by inspection, because any change of a bypass flow rate will be propagated and amplified through the network.

Another important issue in this methodology is the identification of sub-networks. A sub-network is defined as a set of process streams that exchange heat and are independent from the rest of the network. Different sub-networks can share the same utility streams. The number of degrees of freedom must be calculated for each sub-network because in some cases, even if the number of degrees of freedom of the overall network is greater or equal than zero (controllable process), this number may be negative for one of the sub-networks. Due to space limitations, no example will be provided.

An algorithm for identification of loops (independent and dependent), sub-networks, and calculation of the number of degrees of freedom was developed. Those algorithms cannot be presented here due to space limitations. No example can be presented due to the same reason.

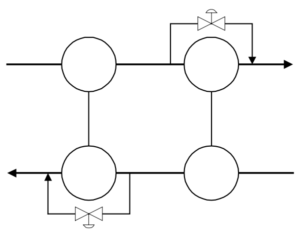


Figure 6. Simple network with one loop

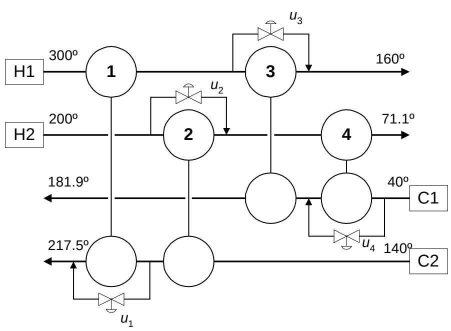


Figure 7. Network with more complex loop

$$RGA = \begin{bmatrix} -2.5802 & 2.2605 & -4.4278 & 5.7474 \\ 0 & -3.3863 & 0 & 4.3863 \\ -8.3232 & 2.1257 & 5.4278 & 1.7697 \\ 11.9034 & 0 & 0 & -10.9034 \end{bmatrix}$$

Heuristic rules

As a result of this work, new heuristic rules for process control of HENs were developed as follows:

a) Calculate the number of degrees of freedom for process control. If it is negative, try to change the design (add heat exchangers) or select which outlet temperatures will not be controlled. If it is greater than zero, investigate the use of the split range control (Glemmestad, 1977), where some heat exchangers can be designed with nominal bypass flow rates equal to zero resulting in capital savings.

b) Do not use the flow division (that is not a bypass stream) in a stream splitter as a manipulated variable.

c) Select the duties of all utility heat exchangers, which have no other downstream heat exchangers, as manipulated variables.

d) Select the duties of process heat exchangers that are closest to the end of the process stream, as manipulated variables.

e) Place the bypass stream on the same side of the stream that must be controlled in a process heat exchanger.

f) Consider the control scheme in the context of the overall process (Luyben et al., 1997). For example, if a reboiler is heat integrated in the network, probably one intrinsic variable of the distillation column should be controlled instead of the reboiler's outlet temperature.

Conclusions

The controllability of HENs was studied in this work. A new degree of freedom analysis was developed that shows if a HEN can be controlled. Steady-state and dynamic simulations were used to develop new simple heuristic rules for process control of HENs.

Acknowledgments

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References

Driedger, W. (1998). Controlling shell and tube exchangers. *Hydrocarbon Processing*, 77 (3).

Glemmestad, B., Skogestad, S., Gundersen, T. (1996). On-line optimization and choice of optimization variables for control of heat exchanger networks. *Computers and Chem. Engng*., 21, S379-S384.

Glemmestad, B. (1997). Optimal Operation of Integrated Processes, Studies on Heat Recovery Systems. *Ph.D. thesis*, Norwegian University of Science and Technology, Trondheim, Norwat.

Glemmestad, B., Gundersen, T. (1998). A Systematic Procedure for Optimal Operations of Heat Exchanger Networks. Third International Conference of Foundations of Computer Aided Process Operations, *AIChE Symposium Series*, 320 (94), Snowbird.

Luyben. M. L., Tyreus, B. D., Luyben, W. L. (1997). Plantwide Control Design Procedure, *AIChE J.*, 43 (12), 3161-3174.

Mathisen, K. W., Skogestad, S., Wolff, E. A. (1992). Bypass selection for control of heat exchanger networks. *Proceedings of ESCAPE-1*, S263-S272, Elsinore.

Oliveira, S. G., Liporace, F. S., Araújo, O. Q. F., Queiroz, E. M. (2001). The importance of control considerations for heat exchanger network synthesis: a case study. *Brazilian J. Chem. Engng*., 18 (02), 195-210.

Svrcek, W. Y., Mahoney, D. P., Young, B. R. (2000). *A Real-Time Approach to Process Control*. John Wiley & Sons Ltd., Chichester.