

Bypass Design for Control and Optimization of Heat Exchanger Networks

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Abstract

Disturbance propagation during a HEN operation may make the control difficult if the HEN is improperly design. Utility flow rates and bypasses are widely used for effective control of process stream target temperatures, but the number of utility units is usually much less than the number of process streams in the network. This paper addresses the optimal bypass design in heat exchanger networks. It consists in a model-based iterative procedure considering a worst-case disturbance rejection with minimum economic penalty. The methodology is demonstrated using a case study with 3 different structures, making possible a comparison between different options on a quantitative basis, taking into account the optimal operation attainable with minimum total annual cost.

Keywords: heat exchanger network control, controllability, bypass design.

1. Introduction

During the last decades, different approaches were proposed to design the control system in order to accommodate setpoint changes and to reject load disturbances in HENs. Mathisen et al. (1992) provided a heuristic method for bypass placement. Papalexandri and Pistikopoulos (1994 a, b) introduced a systematic framework for the synthesis or retrofit of a flexible and a structurally controllable HEN using a MINLP formulation. Aguilera and Marchetti (1998) developed a procedure for on-line optimization and control system design of a HEN also using a MINLP. Yan et al. (2001) proposed a model-based design for the development a retrofit HEN with optimal bypass placement using a simplified model for disturbance propagation and control.

The procedure proposed in this paper is an evolution of the method introduced by Yan et al. (2001). Our approach considers a more rigorous model for the heat exchangers, an algorithm for automatic pairing selection , and additional bypass are included to reduce the utility consume. Two side effects can occur by the bypass HEN control strategy, since usually increases the (i) interaction and (ii) initial investment. This work analyzes the HEN control, bypass design and minimization of utility consumption simultaneously.

2. Operation and Control of HENs

During HEN operation, degrees of freedom or manipulated inputs are needed for control and optimization. In a HEN with n_s streams and n_u utility units, at least $n_u - n_s$ extra

available manipulations must be used to make the operation structurally feasible, where all target temperatures can be controlled independently. We assume in this work that only a single bypass is used and a stream split is not used as a manipulated variable. In order to deal with positive and negative disturbances, the heat exchanger has to be designed with a steady-state flow rate for the bypass stream different than zero.

For a given HEN, a bypass with a specific nominal value u_{nom} can be added without changing the main HEN structure and operating point if the same heat load needs to be maintained. But besides the opportunity to reject disturbances (*i.e.*, $\delta T^t = 0$), its installation must cause an increment of the heat transfer area (*i.e.*, $\delta A/A_0$). A trade-off between disturbance rejection and costs must be considered during the bypass nominal design. Figure 1 illustrates qualitatively how outlet targets temperatures and the increment of area of the bypassed heat exchanger if the same heat load is maintained.

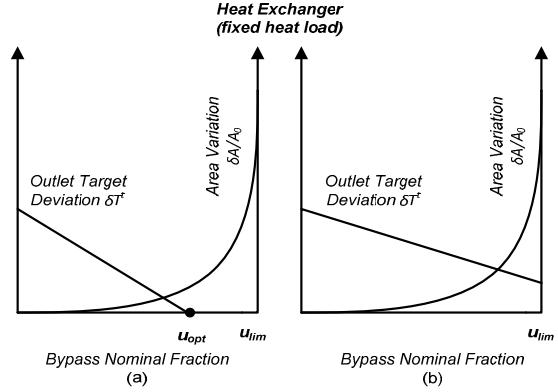


Fig. 1. Qualitative relations between a stream target temperature deviation and the area change as a bypass increases. (a) Complete disturbance rejection when $u_{nom} \geq u_{opt}$; (b) Incomplete disturbance rejection with any bypass fraction.

3. Bypass Design for Control and Optimization

The HEN here is separated into two parts, the inner HEN and the outer HEN according to Glemmestad (1997). While the inner HEN consists of all process exchangers, splitters and mixers, the outer consists of the utility exchangers and target values. The inner HEN contributes with n free variables. For energy optimization the temperatures upstream the utility exchangers, outlets of inner HEN, are to be as close to the stream target temperatures as possible. A model to disturbance propagation and control must characterize the system behaviour under control. It requires a model where the possible control actions are taken into account, represented in matrix form by the equation (1).

$$\delta T^t = G_u \delta u + G_d^t \delta T^s + G_d^w \delta w \quad (1)$$

The vector δT^t correspond to the deviation target temperatures related to the deviations of supply temperatures (δT^s), heat capacity flowrates (δw), and the bypass fraction by the matrices, G_d^t , G_d^w and G_u respectively. The system model for a given configuration is obtained using a heat exchanger model, structural information relating these units and the steady-state data. The unit model is based in the linearization of the model described by the set of equations (2), and (3) in agreement with the representation in Fig. 2.

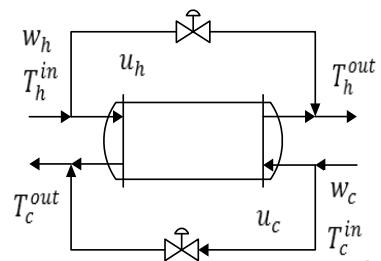


Fig. 2. General structure of a heat exchanger with bypasses.

$$\begin{bmatrix} T_h^{out} \\ T_c^{out} \end{bmatrix} = \begin{bmatrix} \frac{R_h - 1}{R_h - a} (1 - u_h) + u_h & \frac{1 - a}{R_h - a} (1 - u_h) \\ \frac{R_h(1 - a)}{R_h - a} (1 - u_c) & \frac{a(R_h - 1)}{R_h - a} (1 - u_c) + u_c \end{bmatrix} \begin{bmatrix} T_h^{in} \\ T_c^{in} \end{bmatrix} \quad (2)$$

$$R_h = \frac{T_c^o - T_c^{in}}{T_h^{in} - T_h^o} = \frac{w_h(1 - u_h)}{w_c(1 - u_c)} \text{ and } a = \exp\left(\frac{UA}{(1 - u_h)w_h}(1 - R_h)\right) \quad (3)$$

For a given HEN, the vectors $\delta T^{s(+)}, \delta T^{s(-)}, \delta w^{(+)}, \delta w^{(-)}, \delta T_{max}^{t(+)}, \delta T_{max}^{t(-)}$ are defined. It is made the assumption of the worst-case design, i.e. the maximum positive and negative deviations of the HEN target temperatures, which occurs at the extreme disturbance values of supply temperatures and heat capacity flow rates if we consider the linear model (eq.1). It is calculated the maximum positive $\delta T_d^{t(+)}$ and negative $\delta T_d^{t(-)}$ deviations of target temperatures considering no control actions (eq. 4 and 5), and it is determined necessary control correction vectors to each case $d^+ = \delta T_{max}^{t(+)} - \delta T_d^{t(+)}$ and $d^- = \delta T_{max}^{t(-)} - \delta T_d^{t(-)}$.

$$\delta T_d^{t(+)} = G_d^{th} \delta T^{s(+)^h} + G_d^{tc} \delta T^{s(+)^c} + G_d^{wh} \delta w^{(+)^h} - G_d^{wc} \delta w^{(-)^c} \quad (4)$$

$$\delta T_d^{t(-)} = G_d^{th} \delta T^{s(-)^h} + G_d^{tc} \delta T^{s(-)^c} + G_d^{wh} \delta w^{(-)^h} - G_d^{wc} \delta w^{(+)^c} \quad (5)$$

It must be selected the subset of at most n manipulated variables δu_s pairing and the subset of n target temperatures that must be controlled using bypass fraction. The pairing is based on the partial RGA (RGA^\dagger) defined similarly to the regular RGA substituting the inverse matrix by pseudoinverse of the non square gain matrix G_u (Yang *et al.*, 2001). The basic rule is the same as that in regular RGA, where each controlled variable is paired to a manipulated variable such that the corresponding relative gain is positive and as close to 1 as possible. The best combinations are enumerated.

A pair is selected (δu_s) and the necessary control action $\delta u_s^{(+)}, \delta u_s^{(-)}$, is calculated by solving the optimization problem ($\min \|G_u M \delta u_s - d\|_2$) using d^+ and d^- respectively, and the nominal values is updated according to practical limitation ($u_{new} = -\min\{\delta u_s^{(+)}, \delta u_s^{(-)}\}$). The convergence criterion is checked ($|\delta u_{new} - \delta u_{old}| \leq \varepsilon$), where ε is the permissible computational error. The model is retrofitted updating the matrices G_u , G_d^t , and G_d^w with the selected nominal bypasses values and all the procedure is repeated until the convergence. At the end the new areas of heat exchangers bypassed are estimated and the model is used to calculate stream outputs deviations and the utility consumption is estimated to the worst case design. The new Total Annual Cost (TAC) is estimated the procedure must be repeated to other possible pair, the best solution is that with the lower TAC.

4. Case Study

In this section 3 different HENs structure depicted in Figure 3, are used to illustrate the design procedure and make a proper selection. The Table 1 lists the design data and the disturbance information need to compute the worst case design.

The degrees of freedom analysis for the *HEN01*, *HEN02* and *HEN03* pointed out the number of bypasses that can be used for control and optimization for each HEN ($n = 3$), i.e. the dimension of the space spanned by the bypasses in the target temperature set. A common strategy will use only one bypass to control the temperature target of stream if it is not possible using a utility flowrate. For the *HEN01* and *HEN02* only the stream C1 must be controlled using a bypass, and two bypasses will be used during operation to minimize the utility consumption. Considering the potential bypass sequence presented in vector $\delta u = [u_{1,1}^h \ u_{1,1}^c \ u_{1,2}^h \ u_{1,2}^c \ u_{2,1}^h \ u_{2,1}^c \ u_{2,1}^h \ u_{2,1}^c]^T$ the upper limit attainable considering the situation of no driving forces (infinity area) for the *HEN01* is expressed in the vector $u_{lim} = [0.152 \ 0.237 \ 0.495 \ 0.818 \ 0.167 \ 0.083 \ 0.167 \ 0.633]^T$ if is assumed a $\Delta T_{min} = 10^{\circ}C$ the vector $u_{lim} = [0 \ 0.1 \ 0.43 \ 0.79 \ 0.09 \ 0 \ 0 \ 0.56]$. These limits must be considered during the bypass nominal design, associated with a controllability measure to select the appropriated pairing, i.e. taking into account the economic penalty.

With the matrices G_u and RGA^\dagger , the potential manipulated variables are sorted by all positive values as close to one as possible creating a priority order. One could think that if we select the prior pair were the best, but this procedure could result in the selection of the same heat exchanger to be bypassed for different controlled outputs, which would not desirable, since there is only one degree of freedom per exchanger. In addition, even if this pair is a possible one, no economical penalty is considered. But the priority order reduces drastically the number of possibilities to be enumerated, and define an appropriated sequence for this enumeration (probably the best pair will be one of the first). The strategy used here consider that keeping the control of the inner HEN. This strategy implies that disturbances from the inner to the outer HEN when a utility unit is present are permissible, but to reject disturbances the utility consumption may increase if the disturbance combination results in a near worst case scenario.

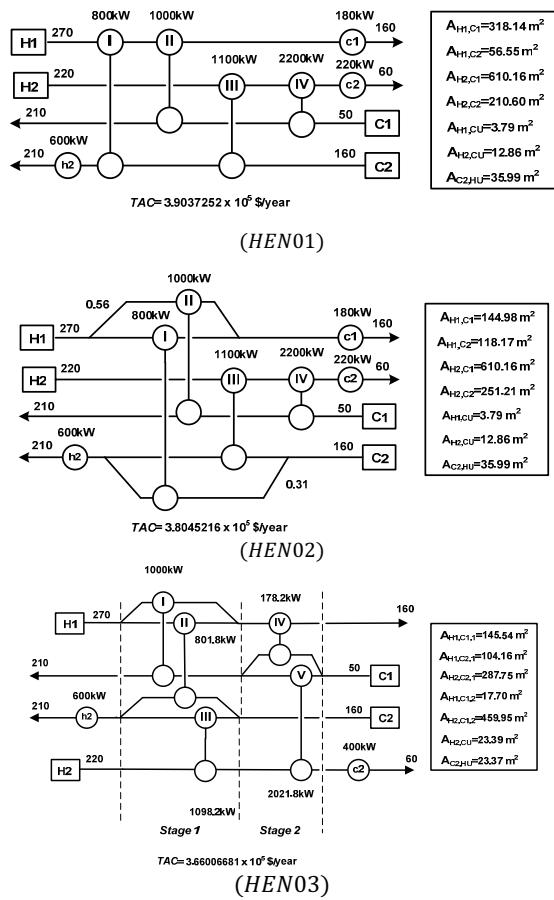


Fig 3. Synthesized HENs for the Case Study using different approaches.

Table 1. Design data for the Case Study.

Stream	T' (°C)	T'' (°C)	F ($\text{kW}^{\circ}\text{C}^{-1}$)	h ($\text{kW m}^2 \text{°C}^{-1}$)	$\delta T^{(+)}$ (°C)	$\delta T^{(-)}$ (°C)	$\delta w^{(+)}$ ($\text{kW}^{\circ}\text{C}^{-1}$)	$\delta w^{(-)}$ ($\text{kW}^{\circ}\text{C}^{-1}$)
H1	270	160	18	1	2	-2	3.6	-3.6
H2	220	60	22	1	2	-2	4.4	-4.4
C1	50	210	20	1	2	-2	4	-4
C2	160	210	50	1	2	-2	10	-10
CU	15	20		1				
HU	250	250		1				

Cost of Heat Exchangers ($\$/\text{m}^2$) = $4000 + 500[\text{Area (m}^2\text{)}]^{0.83}$

Cost of Cooling/Heating Utility = $20 (\$/\text{kW}^{\circ}\text{C}) / 200 (\$/\text{kW}^{\circ}\text{C})$

In order to compare alternatives it is necessary to estimate the range of the utility consumption needed to reject disturbances in the two worst cases. It will provide the range of variation during operation. To avoid this variation, and make a fair comparison between the three alternatives the inner HEN is controlled using as most bypasses as possible according to the rank of the matrix energy balance. The best results obtained to the retrofit of each structure using the bypass design procedure proposed is summarized in the Table 2.

As only 3 bypasses could be manipulated independently, one target temperature is controlled using the utility flow rate, which has been selected based on the cheaper utility. The results show that different investment levels are needed to each case. Comparing the three HENs the last one needs more investment, but the costs associated with the critical consumption assumed by the utility (used to estimate the operating cost) controlled target result in the cheaper solution.

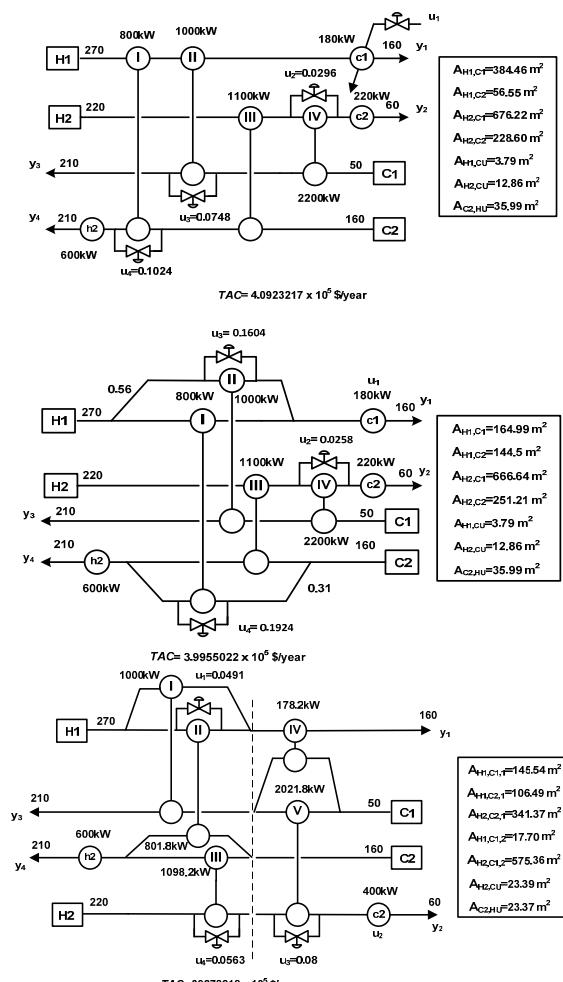


Fig 4. Retouched HENs using bypass design.

Table 2. Bypass Nominal Design for the 3 structures.

<i>Structure</i>	<i>Controlled set</i>	<i>Manipulated set</i>	<i>Nominal Bypass Value</i>	<i>RGA Number</i>	$(\delta A/A_0) \%$	$I-I_0$ (\$/year)	<i>TAC</i> (\$/year)
<i>HEN01</i>	T_{h2}^t	$u_{2,1}^h$	0.0296		20.93		
	T_{c1}^t	$u_{1,1}^c$	0.0748	0	10.85	22506	409294
	T_{c2}^t	$u_{2,2}^c$	0.1024		9.03		
<i>HEN02</i>	T_{h2}^t	$u_{2,1}^h$	0.0258		9.29		
	T_{c1}^t	$u_{1,1}^h$	0.1604	0	18.32	20572	399550
	T_{c2}^t	$u_{1,2}^c$	0.1926		19.23		
<i>HEN03</i>	T_{h1}^t	$u_{1,2,1}^c$	0.0491		3.92		
	T_{c1}^t	$u_{2,1,2}^h$	0.0800	1.44	25.27	25811	392782
	T_{c2}^t	$u_{2,2,1}^h$	0.0563		18.69		

This procedure must reject non controllable HENs, and provide a decision based on the trade-off between controllability and total costs, for this case the cheaper solution shows interaction a little bigger as can be seen by the *RGA* number. The final structures with control schemes are depicted in Fig. 4. For a final decision the dynamic model must be analyzed. The number n is an upper bound on the number of bypasses used to control. The investment cost increases, but it makes possible an operation close to the minimum utility consumption, if the maximum number of bypasses is designed. Therein, there is a trade-off that must be explored.

5. Conclusions

The design of a cost effective HEN capable of being controlled has both economical and operational significance. The controllability depends on the HEN structure, but to be evaluated it is not necessary to design the controller, but it must be selected a set of manipulated and controlled variables. It was presented a systematic model based framework for designing an appropriated control system, selecting the manipulated set, and design bypasses with minimum economic penalty. Through the prediction of the disturbances on controlled variables, it is possible to estimate the bypasses nominal fractions able to reject these disturbances solving an analytical problem per iteration resulting in a fast and robust procedure. The results demonstrate that the 3 structures analyzed are highly controllable with similar total annual cost. In order to make a final decision a comparative controllability analysis including the dynamic performance should be performed.

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