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Operational Controllability of Heat Exchanger Networks

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Abstract: Process integration is motivated from economic benefits, but it also impacts on the plant behavior introducing interactions and in many cases making the process more difficult to control and operate. During the operation utility flow rates and bypasses are widely used for effective control of process stream target temperatures, but the number of utility units is usually less than the number of process streams in the network and some bypasses should be selected. This paper addresses the optimal bypass design for heat exchanger networks. It consists in a model-based iterative procedure considering controllability metrics and worst-case disturbance rejection with minimum economic penalty. This is essentially a piecewise linearization approach producing excellent results. The methodology proposed is demonstrated using a case study with 3 different structures, making possible a comparison among different options on a quantitative basis, taking into account the optimal operation attainable with minimum total annual cost. These results clearly point out for the need of a simultaneous framework for design with controllability and profitability. The main goal of this work is to contribute within the field of optimal operation and control of HENs and the definition of the operational controllability concept.

Keywords: Heat Exchanger Networks, Optimal Operation, Operational Controllability.

1 INTRODUCTION

Operability issues, e.g. flexibility and controllability, are very important for heat integrated process, since the economic performance of a process is greatly affected by process variations and the ability of the system to satisfy its operational specifications under external disturbances or inherent modeling uncertainty. During the operation, a HEN suffers disturbances in the inlet temperatures and heat capacity flow rates. These disturbances propagate through the network and may make the control of process stream target temperatures difficult if the HEN is improperly designed. In order to ensure operability issues for a designed HEN some bypasses with nominal values different of zero must be installed, and possibly the area of the bypassed heat exchanger must be increased to maintain the heat load defined in the design phase. A challenging task is to address the correct placement of the bypass and the number of bypasses to be installed once they affect the flexibility, the controllability, the operating cost and investment cost of the HEN, i.e., a 4 way tradeoff.

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.

In this work, the optimal operation and control strategy for designed heat exchanger networks are investigated and it is proposed a systematical framework where at each iteration a set of bypass candidates are selected and designed feasibly according to the minimum Operational Controllability. In section 2 the optimal operation is defined. In section 3 all components involved in the framework are described and a case study with three different designs is used as background to present the applicability of the method in section 4. Finally, some conclusions are drawn in section 5.

2 OPTIMAL OPERATION AND CONTROL OF HENS

A HEN is considered optimal operated if the targets temperatures are satisfied at steady state (main objective); the utility cost is minimized (secondary goal); and the dynamic behavior is satisfactory (Glemmestad, 1997). To ensure the requirements a control system must be design properly. It involves the control structure selection that shows good controllability according to some metric and also come along the minimization of the economic penalty, i.e with less impact on the energy cost, and on the investment cost if some area must be increased.

During the HEN operation, degrees of freedom or manipulated inputs are needed for control and optimization. The most common options are: (1) utility flowrates; (2) Bypass fraction; (3) Split fraction. Once split fractions may result in competitive effects and possible some RHP-zero, which limit the control bandwidth, only the two first options are addressed in this work. It is rather evident when a utility exchangers take place, in general as the last exchanger for each stream, they fulfill the main pairing rule, i.e. provide a fast and direct effect, with no interaction with other control loops. That is the trivial solution. Thereby, the selection of suitable sets of manipulated variables for controlling the target temperatures is a challenging problem because of its combinatorial nature. Controllability is largely dependent upon its network structure. For HENs a challenging task to be addressed is the correct placement of the bypass, i.e. the location and nominal values in order to reject disturbances.

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. Moreover, 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 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 is maintained. Parallel to the capacity to reject disturbances ($\delta T^t = 0$), it is required an increment of the heat transfer area ($\delta A/A_0$). Therefore, a trade-off between disturbance rejection capacity and investment costs must be considered during the bypass nominal design.

A HEN shows Optimal Operational Controllability if the requirements of optimal operation are accomplished and the control objectives are fulfilled. Next section describes how to redesign a HEN for attaining Operational Controllability.

3 BYPASS DESIGN FOR OPERATIONAL CONTROLLABILITY

For a given disturbance scenario a linearized model can provide an estimation of the maximum static deviation of the system outputs. The model is embedded into a design procedure for optimality selecting bypasses that includes their location and nominal fractions. The linear model considered here is obtained from the model of each unit.

Unit Based Model – A general heat exchanger with bypass on hot and cold side is sketched in Figure 1. Based on the mass and energy balances for the heat exchanger, the mixers and splits, the model described by the set of equations from (1) to (5) can generated in a straightforward manner. The matrices (G_u, G_d^t, G_d^w), are obtained through the linearization of the model HE, using Taylor series expansion, neglecting high-order differentiation terms.

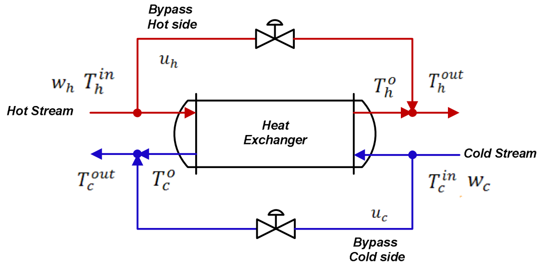


Fig. 1. General structure of a heat exchanger with bypasses.

Unit Model for the system Heat Exchanger with Bypasses.

Mixer Energy Balance:

$$\begin{bmatrix} T_h^{out} \\ T_c^{out} \end{bmatrix} = \begin{bmatrix} 1-u_h & 0 \\ 0 & 1-u_c \end{bmatrix} \begin{bmatrix} T_h^o \\ T_c^o \end{bmatrix} + \begin{bmatrix} u_h & 0 \\ 0 & u_c \end{bmatrix} \begin{bmatrix} T_h^{in} \\ T_c^{in} \end{bmatrix} \quad (1)$$

Inner Heat Exchanger Structure:

$$\begin{bmatrix} T_h^o \\ T_c^o \end{bmatrix} = \frac{1}{(R_h' - a')} \begin{bmatrix} R_h' - 1 & 1 - a' \\ R_h'(1-a') & a'(R_h' - 1) \end{bmatrix} \begin{bmatrix} T_h^{in} \\ T_c^{in} \end{bmatrix} \quad (2)$$

Ratio between effective heat capacity flow rates:

$$R_h' \equiv \frac{(1-u_h)w_h}{(1-u_c)w_c} = \frac{T_c^o - T_c^{in}}{T_h^{in} - T_h^o} \quad (3)$$

Ratio between terminal temperature differences:

$$a' \equiv \frac{T_h^{in} - T_c^o}{T_h^o - T_c^{in}} = \exp\left(\frac{U'A}{(1-u_h)w_h} (1 - R_h') \right) \quad (4)$$

Corrected Global Heat Transfer Coefficient:

$$\frac{1}{U'} = \frac{1}{h_h(1-u_h)^{0.8}} + \frac{1}{h_c(1-u_c)^{0.8}} \quad (5)$$

The differentiation of the previous model in respect to the inlet temperatures, flowrates and bypass fractions result in the following general model for each heat exchanger:

$$\delta T^{out} = G_{u,E}\delta u + G_{d,E}^t \, \delta T^{in} + G_{d,E}^w \, \delta w \quad (6)$$

HEN Model for Disturbance Propagation and Control

If a HEN contains N_e heat exchangers, a system model can be obtained directly by lumping all unit models for a selected sequence of heat exchanger.

$$\delta T^{*out} = G_{u,E}^* \delta u^* + G_{d,E}^{*t} \, \delta T^{*in} + G_{d,E}^{*w} \, \delta w^* \quad (7)$$

The outlet and inlet temperatures flowrates of each heat exchanger is written as a function of the supply and target temperatures and flowrates of the HEN. When the stream is located in between heat exchangers called here as intermediate variables.

The temperature vectors δT^{*out} and δT^{*in} can be ordered according to the supply and target temperatures of the streams that are present in the HEN in the following manner.

$$\delta T^{in} = \left[\delta T_{H1}^S \dots \delta T_{HN_h}^S \, \delta T_{C1}^S \dots \delta T_{CN_c}^S \, \delta T_1^m \dots \delta T_{N_m}^m \right]^T = \left[(\delta T^S)^T (\delta T^m)^T \right]^T \quad (8)$$

$$\delta T^{out} = \left[\delta T_{H1}^T \dots \delta T_{HN_h}^T \, \delta T_{C1}^T \dots \delta T_{CN_c}^T \, \delta T_1^m \dots \delta T_{N_m}^m \right]^T = \left[(\delta T^T)^T (\delta T^m)^T \right]^T \quad (9)$$

The vector δw^* presents N_m redundant heat-capacity flow rates that should be eliminated. This reduces δw^* to $[(2N_e - N_m) \times 1]$. Correspondly,

$$G_u^* = \begin{bmatrix} G_{u,1} \\ G_{u,2} \end{bmatrix} = V_1 G_{u,E}^* V_4 \tag{10}$$

$$G_d^{*t} = \begin{bmatrix} G_{d,11}^t & G_{d,12}^t \\ G_{d,21}^t & G_{d,22}^t \end{bmatrix} = V_1 G_{d,E}^{*t} V_2 \tag{11}$$

$$G_d^{*w} = \begin{bmatrix} G_{d,1}^w \\ G_{d,2}^w \end{bmatrix} = V_1 G_{d,E}^{*w} V_3 \tag{12}$$

Where V_1 to V_4 are the conversion matrices determined by a HEN structure and bypass location. Their derivations are presented in the succeeding section. The reorganized model is equivalent to:

$$\begin{bmatrix} \delta T^T \\ \delta T^m \end{bmatrix} = \begin{bmatrix} G_{u,1} \\ G_{u,2} \end{bmatrix} \delta u + \begin{bmatrix} G_{d,11}^t & G_{d,12}^t \\ G_{d,21}^t & G_{d,22}^t \end{bmatrix} \begin{bmatrix} \delta T^S \\ \delta T^m \end{bmatrix} + \begin{bmatrix} G_{d,1}^w \\ G_{d,2}^w \end{bmatrix} \delta w \tag{13}$$

The preceding model (13) can be separated into two equations, solving the latter to the intermediate temperatures and substituting in the former yields the following model:

$$\delta T^T = G_{u,hen} \delta u + G_{d,hen}^t \delta T^S + G_{d,hen}^w \delta w \tag{14}$$

where

$$G_{u,hen} = G_{u,1} + G_{d,12}^t \left(I - G_{d,22}^t\right)^{-1} G_{u,2} \tag{15}$$

$$G_{d,hen}^t = G_{d,11}^t + G_{d,12}^t \left(I - G_{d,22}^t\right)^{-1} G_{d,21}^t \tag{16}$$

$$G_{d,hen}^w = G_{d,1}^w + G_{d,12}^t \left(I - G_{d,22}^t\right)^{-1} G_{d,2}^w \tag{17}$$

Furthermore, if the vectors of stream temperature and heat capacity flowrates are written based on classification of stream types, the model (14) can be written as

$$\begin{bmatrix} \delta T_h^T \\ \delta T_c^T \end{bmatrix} = G_{u,hen} \delta u + \begin{bmatrix} G_{d,hen,h}^t \\ G_{d,hen,c}^t \end{bmatrix}^T \begin{bmatrix} \delta T_h^S \\ \delta T_c^S \end{bmatrix} + \begin{bmatrix} G_{d,hen,h}^w \\ G_{d,hen,c}^w \end{bmatrix}^T \begin{bmatrix} \delta w_h \\ \delta w_c \end{bmatrix} \tag{18}$$

Network Structural Representation – As stated in the proceeding section, conversion matrices V_1 through V_4 are structure dependent. According to the sequence of equipment considered, the original vector of output temperatures (δT^{*out}) will present a defined order involving the target temperatures (δT^T) and the intermediate temperatures (δT^m).

<u>*Derivation of*</u> V_1. Each element of matrix V_1 has a value 0 or 1 relating the original vector δT^{*out} with the ordered vector δT^{out}. First, the matrix V_1 must have all elements set to 0. The first row of $V_1(i)$ that corresponds to the $\delta T_{h_1}^T$ relation, considering that this target is located in the k position in the disordered vector, set $V_1(i,k)$=1. It should be noted that in case of stream split, where the same temperature enters two or more heat exchangers, there will be more than one position that represent the same target. Then, in a more general way k consist in a vector of corresponding positions. The procedure must be repeated until the last row of δT^{out}.

<u>*Derivation of*</u> V_2. The matrix V_2 is generated analogously to the matrix V_1. Each element of V_2 has a value 0 or 1. The matrix must have all elements set to zero. Select the first column (j) that corresponds to $\delta T_{h_1}^S$ relation, select the k positions that this input appears in the vector δT^{*in} and for each position, set $V_2(k,j)$=1. Repeat the procedure until the last column.

<u>*Derivation of*</u> V_3. Each element of V_3 has a value between 0 and 1. The matrix must have all elements set to zero. Select the first column (j) that corresponds to δw_{h_1}relation, select the k positions that this input appears in the vector δw^* and for each position, substitute by the split fraction of the original stream flowrate, $V_3(k,j) = x_s$. Repeat the procedure until the last column.

<u>*Derivation of*</u> V_4. Each element of V_4 has a value 0 or 1. This matrix is determined by the bypass selection in a HEN, i.e. $\delta u = V_4 \delta u_{sel.}$. If it is desirable a model with all possible candidates, this matrix must be an identity matrix. In order to derive V_4, first all elements must be set to zero. Select the first column (j) that corresponds the first selected manipulated input $\delta u_{sel.}(1)$, select the k position that this input appears in the vector δu, set $V_4(k,j) = 1$. Repeat the procedure until the last column.

Bypass selection based on Controllability metrics – For regulatory purposes and the controllability of the system Kookos and Perkins (2001) proposed a mathematical programming based framework to minimize the overall interaction and sensitivity to disturbances. The resulting MILP model ($P1$) can be used to automatic selection of the optimum set among the potential candidates.

Considering the system generally described by the transfer matrices $y = Gu + G_d d$ with the set i of outputs, set j of inputs, and set m of disturbances. The term $RGA = G \times \hat{G}^{-1}$ presenting the elements λ_{ij} can be used to calculate the $RGA\, number$ defined by (19), which is a measure of diagonal dominance pointing out the overall interaction of the pairs selected while the infinity norm of the matrix $\hat{G}^{-1} G_d$ (20) is related to the sensitivity to disturbances. For controllability purposes, both values must be as close to zero as possible. Solving the problem ($P1$) for the weighting coefficient ρ for assigning the contribution of each term, can be used to select the best pairs according to the controllability metrics.

$$\|RGA - I\|_{sum} = \sum_{i=1}^{ny} \sum_{j=1}^{nu} \mu_{ij} \tag{19}$$

$$\left\|\hat{G}^{-1} G_d\right\|_\infty = \varphi \tag{20}$$

The parameters Ω is a sufficient large number, and $\delta_{i\ell}$ is the Kronecker delta (i.e. 1 if $i = l$, 0 otherwise) and g_{ij} and $g_{d,im}$ the elements of G and G_d respectively. The additional symbols represent auxiliary variables used to compute (19) and (20). The decision variables X_{ij} represent the binary variables that assume value 1 if j is selected to control i, and 0 otherwise.

$$
\left\{
\begin{array}{l}
min \quad J_1 = \rho\varphi + (1-\rho)\sum_{i=1}^{ny}\sum_{j=1}^{nu}\mu_{ij} \\
\sum_{i=1}^{ny} X_{ij} - 1 \leq 0 \\
\sum_{j=1}^{nu} X_{ij} - 1 = 0 \\
\sum_{i=1}^{nu} g_{ij}\,\tilde{g}_{\ell j} - \delta_{i\ell} = 0, \qquad \forall\, i,\ell \\
\left.\begin{cases}
-\Omega\sum_{i=1}^{ny} X_{ij} \leq \tilde{g}_{\ell j} \leq \Omega\sum_{i=1}^{ny} X_{ij} \\
\lambda_{ij} - g_{ij}\tilde{g}_{ij} = 0 \\
\eta_{ij} = \lambda_{ij} - X_{ij} \\
-\mu_{ij} \leq \eta_{ij} \leq \mu_{ij}
\end{cases}\right\} \forall\, i,j \\
\sum_{i=1}^{ny} \tilde{g}_{ij} g_{d,im} - \sigma_{jm} = 0, \qquad \forall\, j,m \\
\left.\begin{cases}
-\epsilon_j \leq \sum_{m=1}^{nd}\sigma_{jm} \leq \epsilon_j \\
\epsilon_j - \varphi \leq 0
\end{cases}\right\} \forall\, j,m \\
X_{ij} = \{0,1\}, \quad \mu_{ij} \geq 0, \qquad \epsilon_j \geq 0 \;\forall\, i,j
\end{array}
\right\} \quad (P1)
$$

Priority Matrix – The application of the model $P1$ can ensure the optimal pair set according to the criteria selected. However its application to HENs requires some additional details in order to ensure the optimal operation.

Feasibility: 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. But besides the opportunity to reject disturbances $(\delta T^t = 0)$, its installation must cause an increment of the heat transfer area $(\delta A / A_0)$. The designer must be aware that the optimal nominal fraction is the lowest value able to provide the total disturbance rejection.

Economic Penalty: different bypasses selection can affect the utility cost in different ways. Therefore the emerging question is how to select the best pairs taking into account that information. The priority matrix proposed by Glemmestad (1997) is used to address this issue.

We can consider the bypass controlled outputs, and the corresponding inner system that has an upstream utility exchanger. Considering the energy balance on the utility exchangers it is possible to put the heat utility loads as a function of bypass fractions:

$$
\begin{bmatrix} \delta T_h^o \\ \delta T_c^o \end{bmatrix} = G_{bp}\delta u; \quad \begin{bmatrix} \delta Q_{HU} \\ \delta Q_{CU} \end{bmatrix} = G_q \delta u \tag{21}
$$

The vector of cost associated with the hot and cold utilities c^T yields $g^{U\$} = cG_q$, which give us the information about how the manipulation of the bypass fractions impacts on the utility cost. Introducing the control error subject to a given output i, e_i, we can define a "priority matrix" P that whose element p_{ij} is the cost to bring the outputs back to its target value.

$$
p_{ij} = -\frac{g_j^{U\$}}{G_{bp,ij}} e_i \tag{22}
$$

The matrix P consists of as many rows as there are controlled temperatures and as many columns as there are inputs that may be manipulated. Therefore, the pairing that results in minimum total utility cost according to P should be selected.

Worst Cases Scenarios – To estimate the priority matrix elements and estimate the bypass nominal value able to reject the disturbances, the errors e must be known. According to Yang et. al (2001) the worst cases form the bypass nominal value point of view based on the constant sign of disturbance propagation in HENs can be defined by the following equations, where the superscript $(+)$ and $(-)$ point out the positive and negative deviations:

$$
\begin{aligned}
e^+ &= \delta T_d^{t(+)} \\
&= G_d^{t\,h}\delta T^{s(+)^h} + G_d^{t\,c}\delta T^{s(+)^c} + G_d^{w\,h}\delta w^{(+)^h} \\
&\quad - G_d^{w\,c}\delta w^{(-)^c}
\end{aligned} \tag{23}
$$

$$
\begin{aligned}
e^- &= \delta T_d^{t(-)} \\
&= G_d^{t\,h}\delta T^{s(-)^h} + G_d^{t\,c}\delta T^{s(-)^c} + G_d^{w\,h}\delta w^{(-)^h} \\
&\quad - G_d^{w\,c}\delta w^{(+)^c}
\end{aligned} \tag{24}
$$

And it is determined the necessary control correction vectors to each case

Nominal Value Estimation – Assuming perfect control for each scenario $(+)$ and $(-)$ and a subset of manipulated variables (δu_s) the bypass fractions need to reject the disturbance loads are $\delta {u_s}^{(+)}/\delta {u_s}^{(-)}$, calculated by solving the optimization problem $(min \;\; \|G_u V_4 \delta u_s + e\|_2)$ using e^+ and e^- respectively. According to the minimum economic penalty the decision must be made according to the equation, and the nominal values is updated according to

$$
u_{new} = -min\{\delta {u_s}^{(+)}, \delta {u_s}^{(-)}\} \tag{25}
$$

In addition for each bypass selected and designed, we must ensure no violation of the upper permissible nominal value given by the equations.

For bypass on hot side:

$$
u_{lim}^k = \frac{T_h^{out,k} - T_c^{in,k} - \Delta T_{min}}{T_h^{in,k} - T_c^{in,k} - \Delta T_{min}} \tag{26}
$$

For bypass on cold side:

$$
u_{lim}^k = \frac{T_h^{in,k} - T_c^{out,k} - \Delta T_{min}}{T_h^{in,k} - T_c^{in,k} - \Delta T_{min}} \tag{27}
$$

The feasibility (areas non infinity) is ensured holding the following constraint:

$$|\delta u_s{}^{(-),k}| + |\delta u_s{}^{(\mp),k}| \leq u_{lim}^k \tag{28}$$

Also a heuristic constraint is added to avoid bypass both sides of the same heat exchanger, which yields singularity. The resulting model $P2$ is described as follows:

$(P2)$ ***Optimal Pairing Selection:*** *(For economic penalty)*

Minimum Utility Consumption (optimal pairing)

$$\min_{X} \sum_{i=1}^{ny}\sum_{j=1}^{nu} p_{ij}^{+} X_{ij} + \sum_{i=1}^{ny}\sum_{j=1}^{nu} p_{ij}^{-} X_{ij}$$

One bypass pr. bypass controlled temperature

$$\sum_{i=1}^{ny} X_{ij} - 1 \leq 0$$

Each bypass can not control more than one output.

$$\sum_{j=1}^{nu} X_{ij} - 1 = 0$$

Reject pairs when $G_{bp,ij} = 0$

$$X_{ij} + g_{ij}^0 \leq 1$$

One degree of freedom per Heat Exchanger

$$\sum_{i=1}^{ny} X_{ij} + \sum_{i=1}^{ny} X_{ij' \neq j} \leq 1$$

Avoiding violation of the upper permissible value

$$\left|\delta u_{hE_i}^{+}\right| + \left|\delta u_{hE_i}^{-}\right| \leq u_{hE_i}^{lim} X_{ij}$$

$$\left|\delta u_{cE_i}^{+}\right| + \left|\delta u_{cE_i}^{-}\right| \leq u_{cE_i}^{lim} X_{ij}$$

Model for Optimal Operational Controllability – Combining the model $(P1)$ and $(P2)$, summing up the objective functions and the two set of constraints result in the complete model for optimal operational controllability. It should be noted that the procedure result in a $MILP$ $(P3)$, which provides the bypass allocation, the nominal values with minimum economic penalty and the controllability metrics.

Optimal Bypass Design – Initialize the bypass nominal values (normally zero for the classic designs methods), the model for disturbance propagation is obtained and the problem (P3) is solved to ensure optimal operational controllability. 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. The convergence is checked ($|\delta u_{new} - \delta u_{old}| \leq \varepsilon$), where ε is the permissible computational error. At the end the new areas of heat exchangers bypassed are estimated (the tradeoff is implicitly considered by the $\Delta T_{\min}$ used in the equations (26) and (27)) 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 is estimated, the best solution is that with the lowest TAC.

Dynamic Modeling – The different retrofitted HENs can be compared in terms of dynamic performance. The dynamic model is obtained modeling N cells according to the equations (29) and (30). The same procedure used to obtain the static model of the system can be used to derive the system dynamic model.

$$\rho_h V_h^i Cp_h \frac{dT_h^i}{dt} = \dot{m}_h Cp_h \left(T_h^{i-1} - T_h^i\right) - UA^i \Delta T_{ef}^i \tag{29}$$

$$\rho_c V_c^i Cp_c \frac{dT_c^i}{dt} = \dot{m}_c Cp_c \left(T_c^{i+1} - T_c^i\right) + UA^i \Delta T_{ef}^i \tag{30}$$

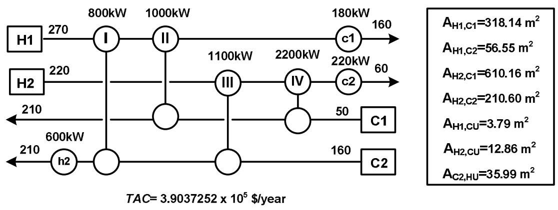
4 CASE STUDY

In this section 3 different HENs depicted in Fig. 2 are used as background. Table 1 list the design data and the disturbance information need to compute the worst case design.

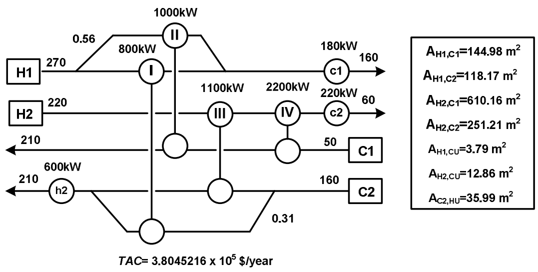
Table 1. Design data for the Case Study.

Stream	T^t (°C)	T^s (°C)	F (kW°C^{-1})	h (kW m^2 °C^{-1})
H1	270	160	18	1
H2	220	60	22	1
C1	50	210	20	1
C2	160	210	50	1
CU	15	20		1
HU	250	250		1

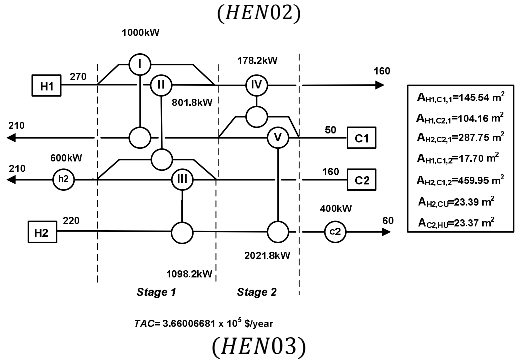
Cost of Cooling Utility = 20 (\$kW^{-1}y^{-1})
Cost of Heating Utility = 200 (\$kW^{-1}y^{-1})
$\delta T^{(+)} = \delta T^{(-)} = 2$ *and* $\delta w^{(+)} = \delta w^{(-)} = 10\%$



$(\boldsymbol{HEN01})$



$(HEN02)$



$(HEN03)$

Fig. 2. HENs Designed for the Case Study u for $\Delta T_{min} = 10$ using different approaches.

For each HEN it was considered the outlet temperatures as controlled variables $\delta T^t = [\delta T^t_{h1} \quad \delta T^t_{h2} \quad \delta T^t_{c1} \quad \delta T^t_{c2}]^T$ and as potential candidates for the bypass controlled targets $\delta u = [u^h_{1,1} \quad u^c_{1,1} \quad u^h_{1,2} \quad u^c_{1,2} \quad u^h_{2,1} \quad u^c_{2,1} \quad u^h_{2,2} \quad u^c_{2,2}]^T$ for the first HEN and amorously for the others. To ensure the structural feasible operation the maximum number of bypasses was installed. The model was solved with $\rho = 0.5$, $M = 100$. The results are summarized in the Table 2.

Table 2. Bypass Nominal Design for the 3 structures.

hen	*y set*	*u set*	*Nom. Values*	*RGA Number*	$(\delta A/A_0)$ %	*TAC ($/y)*
	T^t_{h2}	$u^h_{2,1}$	0.0296		20.93	
01	T^t_{c1}	$u^c_{1,1}$	0.0748	0	10.85	409,294
	T^t_{c2}	$u^c_{2,2}$	0.1024		9.03	
	T^t_{h2}	$u^h_{2.1}$	0.0258		9.29	
02	T^t_{c1}	$u^h_{1.1}$	0.1604	0	18.32	399,550
	T^t_{c2}	$u^c_{1,2}$	0.1926		19.23	
	T^t_{h1}	$u^c_{1,2,1}$	0.0491		3.92	
03	T^t_{c1}	$u^h_{2.1.2}$	0.0800	1.44	25.27	392,782
	T^t_{c2}	$u^h_{2.2.1}$	0.0563		18.69	

One target temperature is controlled using the utility flowrate, it was selected to manipulate the cheaper utility. The results show that different investment levels are needed to each case, since the structure limits the operability as expected. Comparing the three HENs the last one needs more investment, but the previous costs associated with the critical consumption assumed by the utility controlled target (considered to estimate the operating cost) still result in the cheaper solution.

This procedure must reject non controllable HENs, and provide a decision based on the trade-off between controllability and total costs, i.e. the optimal operational controllability. It should be noted that the third structure represent the cheaper solution but the interaction as pointed out by the RGA number was larger. Even tough, the HEN03 presented the best operational controllability. For a final decision, and fulfillment of the third goal in optimal operation of HENs the dynamic model must be analyzed.

In Figure 3, is verified the convergence behavior running the iterative design for the solution shown in Table 2 for the $HEN01$. For a tolerance of 10^{-4} the solution converges after 6 iterations with 3.06 seconds. Increasing the disturbance data by 50% the convergence is achieved with more iterations and 9.32 seconds are needed.

5 CONCLUSIONS

The bypass design for HENs was accomplished through optimal operation problem taking into account the trade-offs between energy cost, investment cost and the controllability in order to ensure an economic operation. The design of a HEN cost effective capable to be controlled has both economical and operational significance. The controllability depends on the HEN structure, but to be evaluated in fact 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 framework model-based to design 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 high controllable with similar total annual cost. In order to make a final decision a comparative controllability analysis including the dynamic performance should be performed.

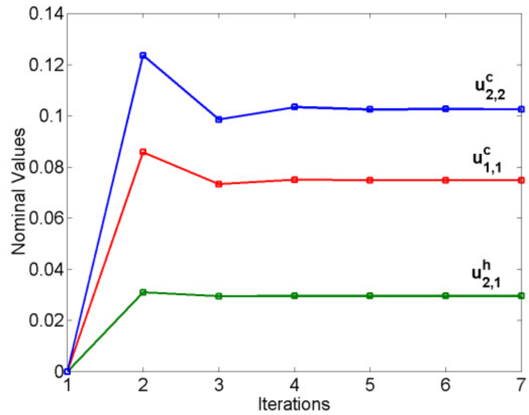


Fig. 3. Iterative Bypass design for $HEN01$ with, T^t_{h2}, T^t_{c1}, T^t_{c2} as bypass controlled.

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REFERENCES

Aguilera, N. and Marchetti, J. L., (1998). Optimizing and controlling the operation of heat exchanger networks. AIChE Journal, 44(5), 1090–1104.

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

Kookos I.K. and J. D. Perkins, (2001). An Algorithm for Simultaneous Process Design and Control. Ind. Eng. Chem. Res. 2001, 40, 4079-4088.

Mathisen K.W., S. Skogestad, and T. Gundersen, (1992). Optimal Bypass Placement in Heat Exchanger Networks,'' AIChE Meeting, New Orleans, LAŽ1992

Papalexandri, K.P. and E.N. Pistikopoulos, (1994a). Synthesis and Retrofit Design of Operable Heat Exchanger Networks. 1. Flexibility and Structural Controllability Aspects. Ind. Eng. Chem. Res. 33 No. 7.

Papalexandri, K.P. and E.N. Pistikopoulos, (1994b). Synthesis and Retrofit Design of Operable Heat Exchanger Networks. 2. Dynamics and Control Structure Considerations. Ind. Eng. Chem. Res. 33 No. 7.

Yan, Q. Z. Y. H. Y and Y. L. Huang, (2001),. Cost-Effective Bypass Design of Highly Controllable Heat-Exchanger Networks, AIChE J., 47(10), 2253-2276.