Controllability and Operability Analysis of Heat Exchanger Networks Including Bypasses

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In this paper, the influence of bypasses in heat exchanger networks on theoretical control properties and closed-loop behavior was investigated. According to theoretical control properties obtained using the singular value decomposition technique, the presence of bypasses increases flexibility of the heat exchanger network. This result was corroborated using closed-loop dynamic simulations using a proportional integral controller and a proportional integral controller with dynamic estimation of uncertainties. The heat exchanger network including bypasses outperformed the dynamic behavior of the heat exchanger network without bypasses. Moreover, closed-loop dynamic responses were improved significantly using controllers with dynamic estimation of uncertainties.

Key words:
Heat exchanger network, control properties, bypasses

Introduction

Due to depletion of oil reserves and increases in the price of energy, important research has been and is currently being carried out in order to efficiently use energy and reduce dependence on oil. For instance, one method employed to reduce energy consumption in chemical plants is the use of heat exchanger networks (HEN), where the main objective is to use hot streams to supply part of the energy required by cool streams. As a result, total energy consumption required is reduced. HENs can be synthesized using the pinch point method, where minimum amounts of cooling water and steam are predicted using thermodynamic calculations[1].

Important work has been done on heat exchanger network synthesis using pinch technology and mixed-integer nonlinear programming techniques.[2,3] The latter method formulates the problem as an objective function that must be minimized or maximized, subjected to some restrictions. The synthesis of optimal HENs can be formulated in two stages: in the first stage the optimal HEN is obtained in terms of minimum total annual cost, and in the second stage the control behaviour is studied in order to determine if the HEN can eliminate disturbances in inputs. Other methods formulate the problem in a single stage using mathematical programming that incorporates control issues. For example, Papalexandri and Pistikopoulos[4,5] developed a systematic framework for the synthesis and/or retrofit of flexible and structurally controllable HENs using a MINLP formulation that includes controllability aspects. They found that the simultaneous consideration of operability aspects and cost optimality at the synthesis and/or retrofit stage accounts properly for the trade-off between proper dynamic behaviour and minimum total annual costs.

Westphalen *et al.*[6] used a controllability index (condition number) to compare the controllability characteristics of different HENs. This controllability index can be useful to detect the optimal HEN in terms of control and heat integration. This is important because heat integration between process streams can lead to integrated processes that are more difficult to control.

Yan *et al.*[7] reported a design procedure to determine optimal bypass locations and nominal fractions for proper disturbance rejection with minimum economic penalties.

Lersbamrungsuk *et al*.[8] showed how, for a given HEN, and with information provided regarding disturbances, the corresponding control structure can be obtained by solving an integer-linear problem.

Controllability analysis and closed loop dynamics for HENs are necessary in order to obtain systems that can be controllable and operable in industrial practice.[9] Hence, the focus of this study is on the use of resiliency analysis to select design configuration and adjust target temperatures when set point changes or disturbances are implemented in the system.

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Singular value decomposition

The singular value decomposition technique (SVD) has been used in control in order to obtain theoretical control properties for complex distillation systems,[10,11] reactors[12] and other control systems.[13,14] This technique requires a small number of open-loop dynamic responses grouped in transfer function matrices. The importance of the SVD technique is that it enables prediction of closed-loop dynamic behavior of the system without dynamic simulations under the action of some specific controller. The SVD technique implies that any complex matrix can be decomposed into three matrices in the frequency domain:

$$G(\omega j) = V(\omega j)\ \Sigma(\omega j)\ W^H(\omega j) \tag{1}$$

where $\Sigma = \text{diag}\ (\sigma_1, \sigma_2, \ldots\ldots, \sigma_n)$, σ_i = singular value of $G(\omega j) = \lambda^{1/2}[G(\omega j) \cdot G(\omega j)^H]$, $\sigma_1 > \sigma_2 > \ldots\ldots > \sigma_n > 0$, $r \leq n$; $\mathbf{V} = (v_1, v_2, \ldots)$ is the matrix of left singular vectors, and $\mathbf{W} = (w_1, w_2 \ldots)$ is the matrix of right singular vectors. Two parameters of interest in chemical process control are the minimum singular value (σ_*) and the ratio of maximum to minimum singular values, or condition number (γ^*):

$$\gamma^* = \frac{\sigma^*}{\sigma_*} \tag{2}$$

The minimum singular value is a measure of the invertibility of the system, and it has been associated with potential problems of the system under the action of feedback controllers. The condition number represents the sensitivity of the system under uncertainties in process parameters and modeling errors. Systems with high σ_* values and low γ^* values are preferred because, from a physical point of view, low minimum singular values and high condition numbers imply large movements in the control valves for changes in the set points and load rejection. It is important to highlight that controllability analysis refers to the study of the theoretical control properties (minimum singular value and condition number) in order to obtain the intrinsic control properties of a given system without introducing any controller. In contrast, the study of the closed-loop behavior of a system under the action of a specific controller is called operability analysis.

Closed-loop dynamic behavior

As described in the preceding section, the SVD technique enables prediction of closed-loop dynamic behavior; in general, however, to reinforce SVD results, it is necessary to obtain representative closed-loop dynamic responses for both set point tracking and load rejection for a specific controller, e.g., a proportional integral (PI) controller. A PI controller can give good dynamic responses for the control of many processes; if better dynamic response is needed in the system, another controller can be used. A controller that has been successfully implemented to control compositions of products of fully thermally coupled distillation is the proportional integral controller with dynamic estimation of uncertainties (PII) reported in Álvarez-Ramírez *et al.*[15] The transfer function of this controller is expressed in eq. (3); for the deduction, the reader is referred to the work of Álvarez-Ramírez *et al.*[15]

$$C(s) = K_C\left[1 + \frac{1}{\tau_I s} + \frac{K_e}{s(s+g_1)}\right] \tag{3}$$

In eq. (3), proper values of K_C, τ_I, K_e, and g_1 are required to test the performance of the controller. When the third part of the sum in brackets is eliminated, the controller is equal to the PI controller.

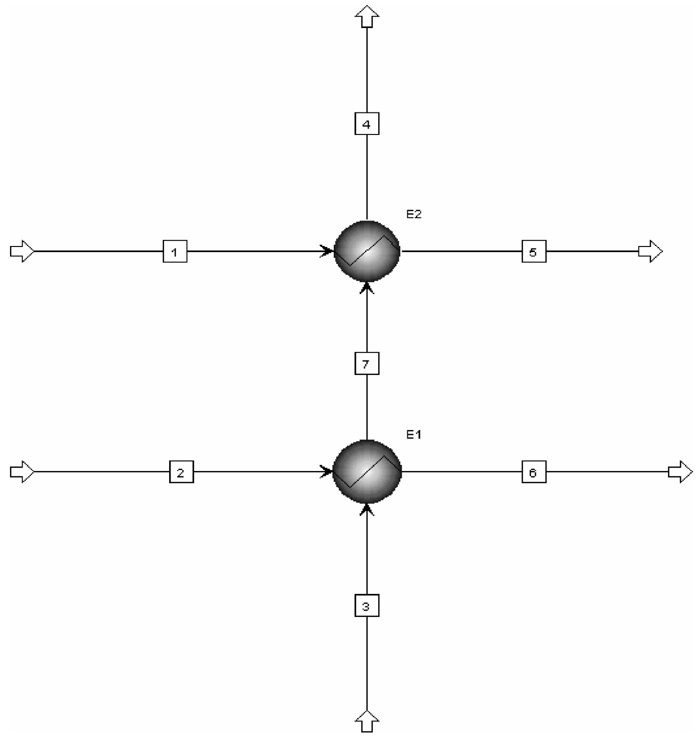
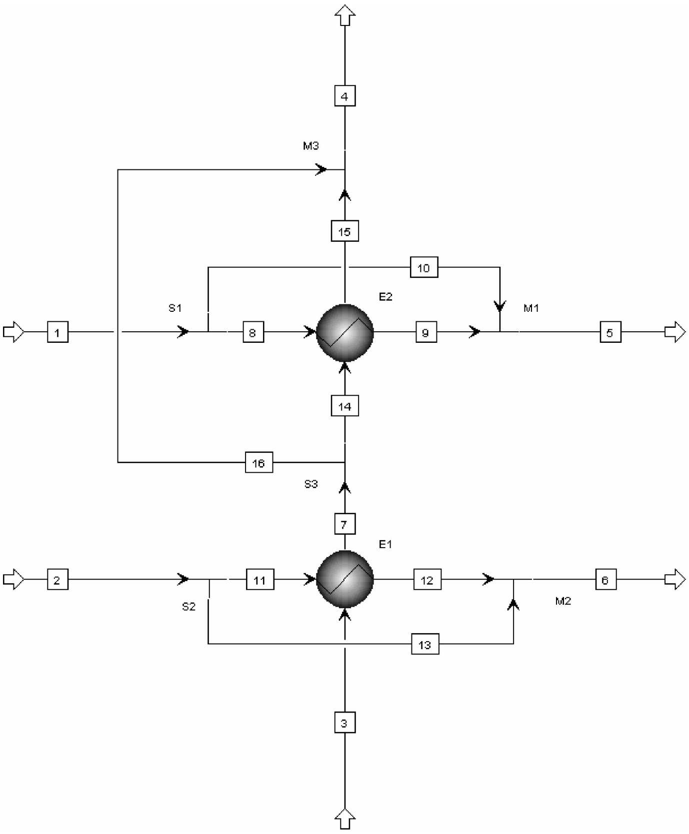


Fig. 1 – *Heat exchange network without bypasses (HEN-1)*

Case studies

We have studied two previously synthesized HENs[16] by pinch analysis for the streams indicated in Table 1. One of the schemes (HEN-2, Fig. 2)



F i g . 2 – *Heat exchange network including bypasses (HEN-2)*

T a b l e 1 – *Stream data for the HENs*

Stream	Inlet temperature, K	Outlet temperature, K	$W \cdot c_p$, kJ h^{-1}K^{-1}
1	558.15	418.15	97779.3
2	373.15	323.15	91138.9
3	313.15	395.35	222098.9

considers bypasses, and the second one (HEN-1, Fig. 1) does not. The study was conducted in two stages. In the first stage, we modeled the HENs using Aspen Plus™ in order to study steady state behavior; in the second stage, we analyzed control properties by using the singular value decomposition technique and closed-loop responses considering conventional proportional integral controllers (PI) and proportional integral controllers with dynamic estimation of disturbances (PII).

Results

The results are presented in two sections. The first presents the theoretical control properties obtained using singular value decomposition of the open-loop transfer functions of the two HENs, and the second part contains a comparison of the closed-loop dynamic responses of the HENs using simple proportional integral controllers and improved closed-loop dynamic responses using a proportional integral controller with dynamic estimation of uncertainties.

Theoretical control properties

As described in the explanation of the use of SVD analysis, open-loop dynamic responses were obtained in Aspen Dynamics™ by implementing step changes in the input variables, and registering and fitting the dynamic responses to linear models. These models can also be obtained from engineering principles (mass and energy balances).

Tables 2 and 3 present the open-loop transfer function matrices for HEN-1 and HEN-2, respec-

T a b l e 2 – *Transfer function matrix for HEN-1*

$$\begin{bmatrix} T_4 \\ T_5 \\ T_6 \end{bmatrix} = \begin{bmatrix} \dfrac{0.2627}{0.09s+1} & \dfrac{0.244}{0.00314s^2+0.392s+1} & \dfrac{0.4083}{4.9\cdot 10^{-3}s^2+0.49s+1} \\ \dfrac{4.238}{0.006s+1}-\dfrac{3.854}{0.023s+1} & \dfrac{5.58}{0.003s+1}-\dfrac{5.353}{0.015s+1} & \dfrac{6.647}{0.005s+1}-\dfrac{6.267}{0.02s+1} \\ 0 & \dfrac{0.1936}{0.015s+1} & \dfrac{0.844}{0.14s+1} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix}$$

T a b l e 3 – *Transfer function matrix for HEN-2*

$$\begin{bmatrix} T_4 \\ T_5 \\ T_6 \end{bmatrix} = \begin{bmatrix} \dfrac{0.2613}{0.09s+1} & \dfrac{0.243}{0.00314s^2+0.392s+1} & \dfrac{0.4109}{4.9\cdot 10^{-3}s^2+0.49s+1} & \dfrac{5.097}{0.03s+1}-\dfrac{5.17}{0.13s+1} & \dfrac{5.16}{0.03s+1}-\dfrac{5.17}{0.13s+1} & \dfrac{5.29}{0.03s+1}-\dfrac{5.12}{0.13s+1} \\ \dfrac{2.122}{0.005s+1}-\dfrac{2.8097}{0.03s+1} & \dfrac{0.1989}{0.015s+1} & \dfrac{3.068}{0.0024s+1}-\dfrac{4.511}{0.025s+1} & \dfrac{57.54}{0.0027s+1}-\dfrac{96.005}{0.03s+1} & \dfrac{61.39}{0.0033s+1}-\dfrac{97.86}{0.03s+1} & \dfrac{61.47}{0.0033s+1}-\dfrac{97.87}{0.03s+1} \\ 0 & \dfrac{2.578}{0.001s+1}-\dfrac{3.883}{0.025s+1} & \dfrac{0.838}{0.14s+1} & 0 & \dfrac{0.1022}{0.001s+1} & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}$$

tively; as it can be seen, dynamic responses were fitted to first order models, second order models and first order models in competence. Moreover, it is important to mention that in the case of HEN-2 we have six input variables, three associated with bypass opening fractions. The SVD was carried out in Matlab™.

Figs. 3 and 4 show theoretical control properties in the frequency domain, i.e., clear trends are observed in the minimum singular value and condition number. Fig. 3 displays a clear tendency in minimum singular values; HEN-2 shows higher values of the minimum singular value for the complete frequency in comparison to the values corresponding to HEN-1. In terms of control, we can say that the HEN involving bypasses will exhibit better closed-loop dynamic responses than those without bypasses for a properly tuned controller for the same set point change in the output temperatures. Analysis of condition number (Fig. 4) reveals that the HEN without bypasses is better conditioned than that with bypasses for low and intermediate frequencies, but at higher frequencies, the opposite result is obtained, i.e., the HEN with bypasses is better conditioned to the effect of disturbances and modeling errors. Thus, according to the condition number, the HEN with bypasses is only better conditioned at high frequencies.

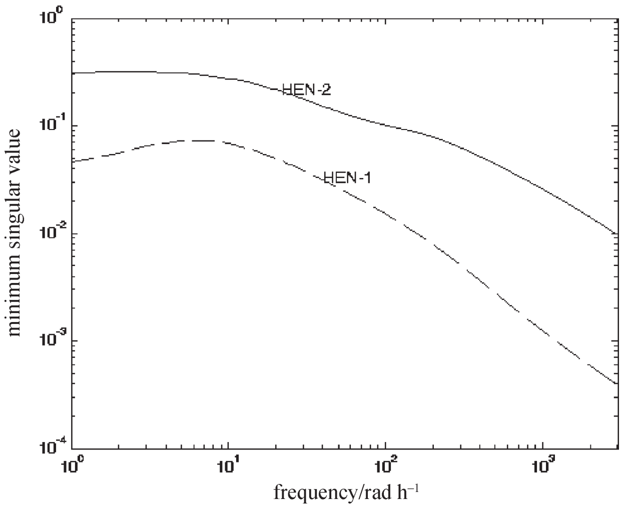


Fig. 3 – *Minimum singular values for the HENs*

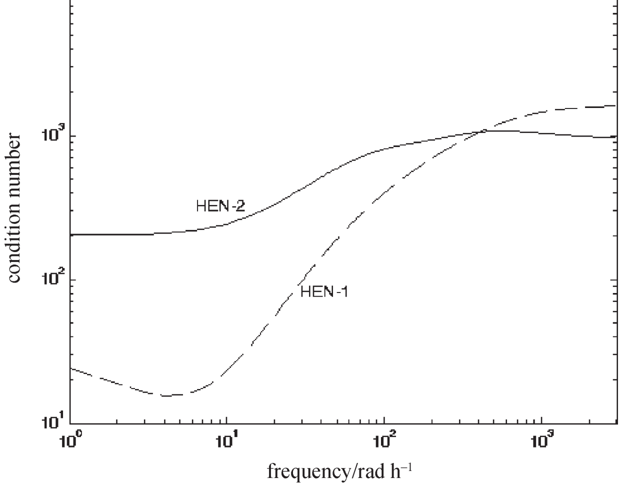


Fig. 4 – *Condition numbers for the HENs*

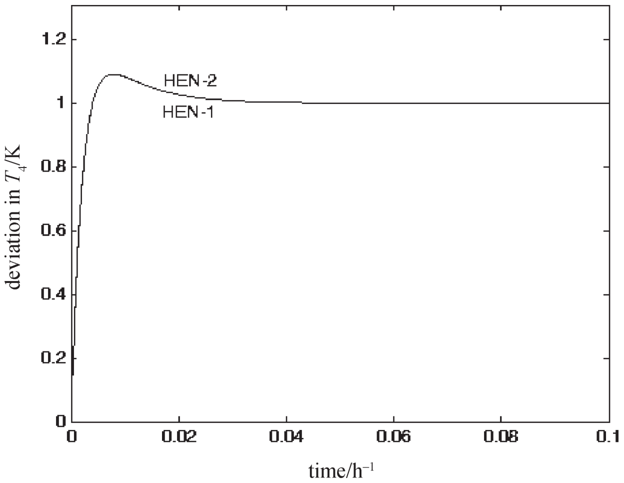
From singular value analysis, one may conclude that the incorporation of bypasses improves the control properties of the HEN. HEN-2 presented higher minimum singular values for the complete range of frequencies and lower condition numbers as frequency was increased. Therefore, HEN-2 is expected to exhibit better dynamic responses than HEN-1 when both are subjected to set point changes or disturbances. Also, lower effort in control valves is expected in the case of HEN-2, compared to HEN-1, i.e., fewer deviations in the control valves compared to nominal operation.

The importance of the SVD technique is the prediction of closed-loop dynamic behavior with a small number of open-loop dynamic simulations. In order to show the consistency between the control properties obtained through the use of the SVD technique and the predicted closed-loop dynamic behavior, several dynamic responses under the action of a specific controller can be obtained.

Closed-loop dynamic responses

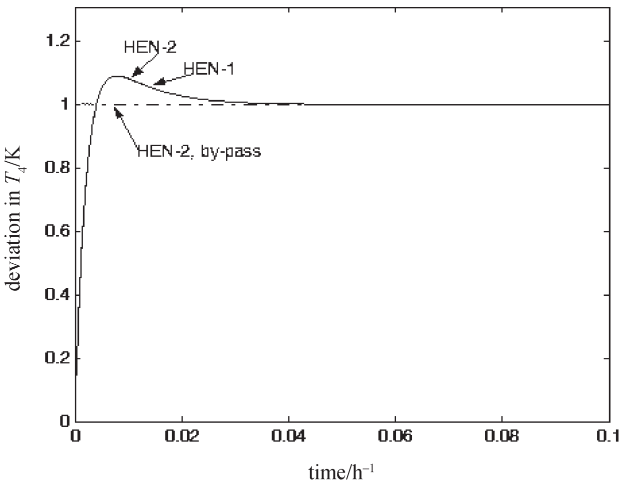
In order to complete the study, closed-loop dynamic responses were obtained for set point changes in target temperatures and disturbances in source temperatures, considering both PI and PII controllers. The results obtained in the SVD section are important because they allow reduction in the number of closed-loop scenarios studied. Indeed, closed-loop dynamic responses are obtained in order to give physical meaning to the theoretical control properties. As a result, only a small number of closed-loop dynamic simulations are presented. Closed-loop dynamic responses were obtained in Simulink™.

Fig. 5 presents the closed-loop dynamic responses for a positive set point change of magnitude 1 K in the output temperature (T_4) for PI controllers in both HENs. Loops were established between the output temperatures T_4 and the input temperatures T_1. It is important to mention that this configuration is difficult to implement in practice, because it is necessary to change input tempera-



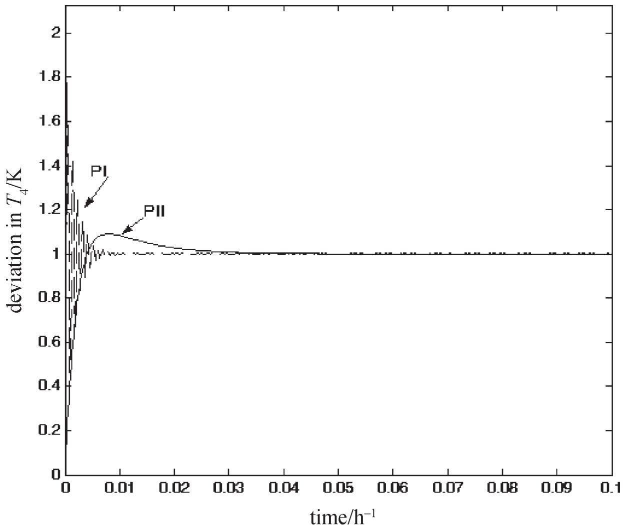
F i g . 5 – *Positive set point change of magnitude 1 K in T_4 in the two HENs*

tures. This figure shows that both HENs can achieve the change in set point, and the closed-loop dynamic responses are very similar. Bypasses in HEN-2 are important because a pairing between T_4 and the opening of the bypass S_1 can be established. This closed loop can easily be established in industrial practice. Additionally, Fig. 6 presents the closed-loop response when the opening of bypass S_1 is manipulated to control temperature T_4. It can be seen that the manipulation of bypass S_1 allows us to achieve the new set point in a very short time in comparison to the other two pairings in the control loops.



F i g . 6 – *Positive set point change of magnitude 1 K in T_4 in the two HENs, and manipulating the opening of the bypass S_1 in HEN-2*

According to the SVD analysis, HEN-2 presents better theoretical control properties than HEN-1; therefore, the preferred HEN is HEN-2. This HEN was subjected to both a positive set point



F i g . 7 – *Closed-loop dynamic responses for PI and PII controllers*

change of magnitude 1 K in T_4 and a disturbance of 5 % reduction in the heat transfer coefficient of the heat exchanger. For this scenario, Fig. 7 presents the comparison of the PI and PII controllers; as can be appreciated, the PII controller outperformed the response of the PI controller. This result is consistent with the fact that the PII controller possesses a term that estimates load disturbances.

Conclusion

Theoretical control properties and dynamic closed-loop behavior of a HEN including bypasses were obtained and compared with those of a HEN without bypasses. SVD analysis demonstrated that the presence of bypasses in the HEN improved theoretical control properties. Also, when both HENs were studied with PI controllers, the results indicate that, for set point changes and disturbances, the HEN involving bypasses reaches the new steady state faster than the HEN without bypasses. Furthermore, it was observed that the PII controller improved dynamic responses significantly, when compared to those obtained with a simple PI. In summary, our study shows that the presence of bypasses and the use of the PII controller improved the control properties of the HEN.

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Nomenclature

$C(s)$ – transfer function of the PII controller in Laplace's domain
c_p – heat capacity, kJ kg^{-1} K^{-1}
$G(\omega j)$ – matrix transfer function in the complex domain
g_1 – adjusted constant
K_c – proportional gain
K_e – adjusted constant
M_1 – mixer point 1
M_2 – mixer point 2
M_3 – mixer point 3
PI – proportional integral controller
PII – proportional integral controller with dynamic estimation of uncertainties
r – rank of matrix **G**
S_1 – opening fraction of bypass 1
S_2 – opening fraction of bypass 2
S_3 – opening fraction of bypass 3
T – temperature, K
$V(\omega j)$ – matrix of left singular vectors in the complex domain
W – mass flow, kg h^{-1}
$W^H(\omega j)$ – transposed conjugated matrix of right singular vectors in the complex domain
$\Sigma(\omega j)$ – matrix of eigenvalues in the complex domain
σ_i – singular values
σ_* – minimum singular value
σ^* – maximum singular value
γ^* – condition number
τ_I – integral time

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