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Low-level flexible-structure control applied to heat exchanger networks

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Abstract

A low-level flexible-structure control is proposed for designing control systems capable of efficiently handling constraints on the manipulated variables of heat exchanger networks (HENs). Flexible-structure refers to the capability of the resulting control system to switch from one closed-loop structure to another in order to keep regulation, and low-level means that it can be configured in most distributed control systems. This control approach is useful to hold the operating point close to an optimum when optimal conditions are located on the constraints. The application example compares the approach with the use of a more involved strategy.

Keywords: Flexible-structure control; Control constraints; Heat exchanger networks; Near optimal operation

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1. Introduction

1.1. Constraints on manipulated variables

The multi-loop control structure is still the most frequent and popular control structure found in most chemical process plantwide applications. This is basically because most of the real process control problems involve several controlled and manipulated variables, and because of a still slow spread of multivariable control techniques to applications. Selecting the right pair of variables in these problems is mostly decided by dynamic considerations and attending to the interactions among closed loops. In fact, several model-based methods are available to synthesize low interactive multi-loop control systems in a rational fashion. However, quite frequently process control engineers face the problem of including hard constraints on one or more control variables. As soon as constraints on manipulated variables appear, the operability space of the whole process system must be revised and often the designed control system must be modified.

In practice, any manipulated constraint known in advance leads process operators to take actions to keep the system away from an uncontrolled condition. These actions reduce the operation space, and typically hold the process at less efficient operating points. Hence, the need for finding a way for broadening controlled operation spaces has stimulated the search for flexible control system structures. Since a considerable effort is made to obtain flexible process designs capable of efficiently covering several operating conditions, it is necessary to make sure that the control system does not reduces such flexibility.

Most of the recent literature dealing with constraints in manipulated variables investigates the solution to the general problem through a mix of predictive and optimizing formulations. In particular, constrained model predictive control (MPC) uses a dynamic model of the controlled process to perform constrained on-line optimization at predetermined time instants. The approach is quite attractive since potential operating difficulties caused by manipulation constraints can be detected an solved in advance. The alternative proposed in this article is a practical solution that could be classified as a low-cost control technique since it can

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be commissioned by simple configuration in any distributed control system (DCS).

1.2. Control of heat exchanger networks

In heat exchanger networks (HENs), hard constraints on manipulated variables rise as a natural and frequent part of the control problem. This is particularly true when moving the system from an operating point to another at full capacity, or during shut down.

The problem of finding proper control structures capable of achieving the regulation objectives in HENs have been addressed in several key articles (Marselle, Morari, and Rudd, 1982; Beautyman and Cornish, 1984; Calandranis and Stephanopoulos, 1988; Huang and Fan, 1992; Mathisen, Skogestad, and Wolf, 1992). Lately, Aguilera and Marchetti (1998) proposed a method for on-line optimization and control of HENs, and discussed the degrees of freedom with respect to the optimization problem. Also, Glemmestad, Skogestad, and Gundersen (1999) presented an alternative approach for optimal operation of HENs based on periodic steady-state optimization and a fixed control structure selected prior to the operation.

1.3. Objectives

This work takes a different approach to define an optimizing control system for HENs based on a flexible-structure control scheme (FSC) designed to handle constraints on manipulated variables. Here the problem is solved by a convenient combination of control loops selected through a non linear function, or by switching control structures when the main controller signal overflows from a constraint model.

Defining more than one flexible-structure control loop in the multiple-input multiple-output (MIMO) scenario presented by an HEN system can be viewed as an advanced extension of the traditional multi-loop control structure. In this proposal, the optimizing nature of the operation is maintained via an adequate selection of the sequence in which the manipulated variables are activated. The application to HENs shows that selecting the right manipulated variables for a given control target and using auxiliary variables only when necessary, helps to keep the operation close to the optimum.

Hence, this article is aimed at providing the conceptual elements for synthesizing FSC systems capable of working very close to optimal manipulated constraints by using auxiliary control variables which extend the controllability space. In particular, the work focuses on defining FSC systems for the optimal constrained operation of HENs.

The organization of this paper is as follows: Section 1 describes the main ideas supporting FSC and discusses some heat-exchanger configuration patterns where they can be applied; these patterns can also be viewed as subsystems for more involved HENs. It also gives a general procedure to define and tune the controllers included in the structure. Section 2 discusses the main features and conditions for the optimal operation of HENs and recalls main concepts useful for configuring the whole HEN control system. An application example is analyzed in Section 3, where the reasons for the achieved heat integration are discussed and several results of dynamic simulations are presented. Concluding remarks are given in Section 4.

2. Flexible-structure control

2.1. Pairs of associated manipulated variables

Block diagrams are simple and effective means for describing process structures even when nonlinearity is present in the actual plant. Fig. 1 shows the structure of the basic process system to implement flexible-structure control. The first special feature to be noted is that the output variable y may be controlled by either u_1 or u_2 through different dynamic elements $Gp_1(s)$ and $Gp_2(s)$. The second feature is that, assuming u_1 to be the preferred or primary manipulated variable, a hard constraint might become active for extreme values of this variable. If u_1 eventually saturates, u_2 may be used as an auxiliary or second manipulated variable for keeping the system under regulation. Notice that $Gp_1(s)$ and $Gp_2(s)$ might involve pieces of process equipment which might not necessarily be located in physical proximity.

Figs. 2–5 give few examples of representative association of manipulated variables in HENs. In all these figures T_{h1} is the controlled variable, u_1 is the main manipulated variable and u_2 is the auxiliary variable. The simplest cases are given by the heat exchangers in series indicated in Figs. 2 and 3, where the intermediate heat exchangers, shown in dash lines, might be present. These arrangements are very common when, besides the task of reaching a final temperature target on a process stream (in this case h_1), there is an extra goal such as maximum energy recovery. Heat exchangers (I_1 and I_i) are units specifically designed for recovering the excess energy in the process stream h_1. The service equipment

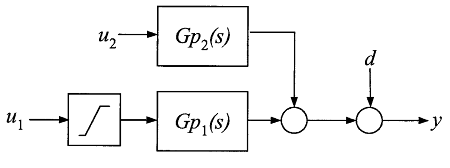

Fig. 1. Process structure denoting association of a pair of manipulated variables.

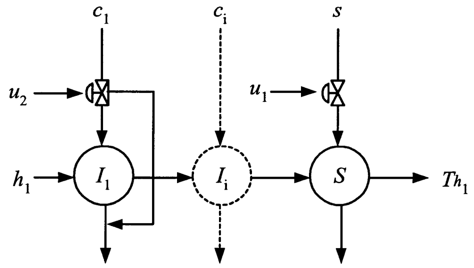

Fig. 2. The bypass can protect the cooling flowrate from saturation at the lower bound.

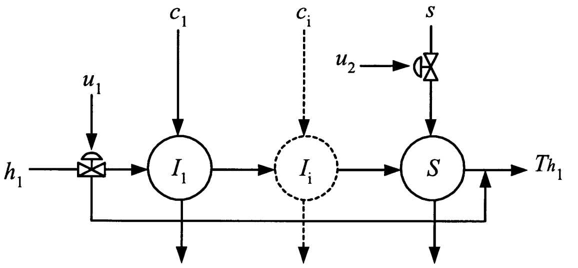

Fig. 3. The cooling flowrate can protect the bypass from saturation at the lower bound.

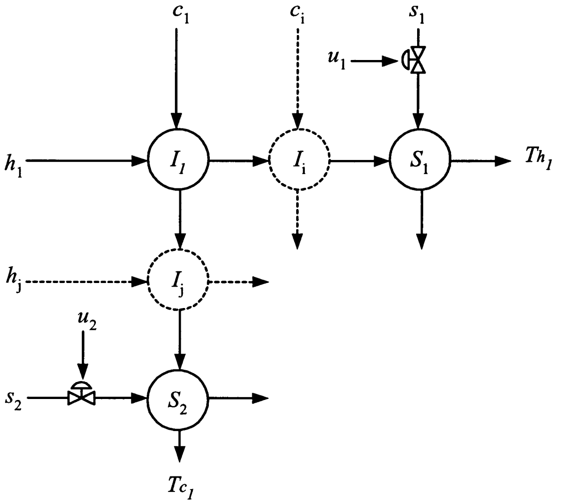

Fig. 4. The heating utility might protect the cooling frowrate from closing completely.

(S) completes the thermal conditioning using a utility stream.

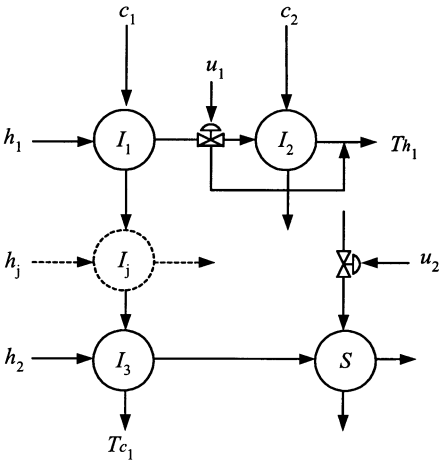

Fig. 5. The cooling flowrate might protect the bypass from a completely-close saturation.

Adopting the manipulated-variable configurations in Fig. 2 or Fig. 3 depends on how the system is expected to work under normal conditions for maximum energy recovery or minimum utility usage. The configuration in Fig. 2 is mostly used when the service S operates permanently or almost permanently and the bypass ratio u_2 operates closed or almost closed. Hence the bypass ratio is activated only if the service flow rate u_1 tends to close down in response to a cold disturbance. The design of Fig. 3 is preferred when the service equipment must operate intermittently. In this case the preferred manipulated variable is the bypass ratio u_1 which might call for assistance from the service equipment S if an important hot disturbance comes in. Note that normally u_1 should work near the completely-closed position for maximum heat recovery.

Though somewhat more involved, the systems in Figs. 4 and 5 show analogous associations among control variables for flexible-structure loops. The case in Fig. 4 assumes that the final temperature T_{h1} is controlled primarily using the utility stream s_1; however if significant cold disturbance comes into the network, the heater S_2 must be turned on to allow controlled operation. A similar reasoning is used in Fig. 5 where a hot disturbance might close completely the bypass u_1 and the assistance is required from the cooler S. The comments in this paragraph assume that the outlet temperature T_{c1} is controlled by a multibypass or a bypass on the I_1 exchanger.

A goal of this article is to show that using an appropriate low-level control system on these HEN configurations, it is possible to achieve temperature regulation at the outlet streams while at the same time addressing the energy recovery problem.

2.2. Flexible-structure loops

The control problem in question requires an appropriate design which must include the dynamics involved of the system and, if possible, it must allow the operator to handle the balance between control quality and energy integration. Very frequently, efficiently solving input constraint problems requires a process engineering approach capable of combining control and process efficiency.

Consider a controller $C_1(s)$ included in Fig. 2 to adjust the manipulated variable $u_1(s)$ and control $y(s)$ at a given setpoint value r. Then the stationary value expected for the controlled variable is $Gp_1(0)u_1(0)$, and if an integral mode is included, the final value of the manipulated variable is $u_1(0) = Gp_1^{-1}(0)r$. Note also that the quantity $Gp_1(0)u_1(0)$ may represent—or it is proportional to—the energy administrated by the regulating system to take the controlled temperature to its target. Hence, if only a fraction of this energy can be handled through the manipulated u_1 (this implies that a control constraint is activated at a given requirement level), and the additional capacity can be provided through the variable u_2, then, there are at least two alternatives for defining the protection of both regulation and operability:

1) Preventive protection: given a total energy requirement $Gp_1(0)u_1(0)$ and the upper bound $\bar{u}_1$, a proportion $\eta\ Gp_1(0)[u_1(t) - \kappa]$ with $\eta \in [0, 1)$, $\kappa \in [0, \bar{u}_1]$, is provided by the subsystem Gp_2 previous to the saturation of $u_1(t)$.
2) Reactive protection: given the controller output $u_1(t)$ at an operating point such that $|u_1(t)|>\bar{u}_1$, the subsystem $Gp_2(s)$ provides the complementary energy $Gp_1(0)[u_1(0) - \bar{u}_1]$ required to reach the target r.

Using this reasoning, a flexible structure control is proposed by Giovanini and Marchetti (2000) for handling both types of protections based on the following nonlinear decision function:

$$f(u_1) = \begin{cases} u_1(t) - \bar{u}_1 + \eta(\bar{u}_1 - \kappa) & \bar{u}_1 \le u_1(t) \\ \eta(u_1(t) - \kappa) & \kappa < u_1(t) \le \bar{u}_1 \\ 0 & 0 \le u_1(t) \le \kappa \end{cases} \qquad (1)$$

where

$$0 \le \eta \le \min\{1, \eta_{\max}\}; \quad 0 \le \kappa \le \bar{u}_1$$

Fig. 6 shows how the controller $C_1(s)$ is combined with the controller $C_2(s)$ through $f(u_1)$ to determine the auxiliary control action. The parameter κ included in the above formulation is used to start the preventive protection from a given value $u_1(t) = \kappa$. More explicitly, if $\kappa = 0$ this protection is permanent along the whole span of $u_1(t)$, and if $\kappa = \bar{u}_1$ there is not preventive protection at all. The reactive protection starts when $u_1(t) > \bar{u}_1$, i.e. once that $u_1(t)$ saturates.

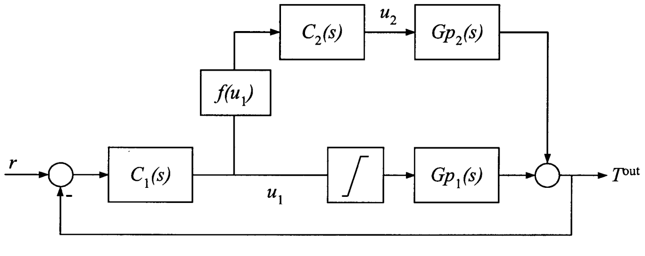

Fig. 6. Flexible-structure control.

Notice that: (i) for $u_1(t) \le \bar{u}_1$, $\kappa \ne 0$ and $\eta \ne 0$, both manipulated variables actuate simultaneously on the same controlled variable; and (ii) when $\eta = 0$ the best possible result is obtained from the energy integration point of view since the auxiliary variable is used to cover energy demands when the main manipulated variable is unable to provide it alone. If $\eta > 0$ the auxiliary variable u_2 is used to prevent the saturation of u_1 before reaching the saturation value $\bar{u}_1$; this preventive task is done with an intensity proportional to parameter η. Avoiding saturation of u_1 might be a desirable feature for the control system since this tends to keep the fastest loop working to ensure a better control quality, however, this is done at expense of energy integration.

Note also that the second controller $C_2(s)$ is included for better dynamic adjustment of the secondary manipulated variable u_2. From inspection of Fig. 6 and the decision function $f(u_1)$ it is clear that a change in the control structure occurs when $u_1(t) > \kappa$, or as soon as $u_1(t)$ saturates at the value $\bar{u}_1$. Under the latter condition, the equipment in charge of the regulation is associated to the process part represented by Gp_2, while the original control loop remains open or no operative.

Regarding the actuator dynamics, it is interesting to observe that for $\eta = 0$ the control action is executed over a divided range; that is, the second actuator starts moving after the first one stops. For positive values of η, the control action is executed simultaneously by both actuators over a common range but in opposite directions since, when one valve closes the other one opens. The amplitude of the common range is handled through the parameter κ, and the intensity by parameter η.

2.3. Controller design and tuning

Besides the underlying optimization problem that might be associated with the selection of parameters κ and η, a most important part of the problem is the development of a systematic method for designing and tuning the controllers involved in the control system. Note that flexibility arises from the capability to switch from one control loop to another. To this end, let us analyze each possible control condition separately: (i) the first control condition—or control structure—occurs when only $C_1(s)$ is deployed for regulation, i.e. when $\eta = 0$ and $u_1(t)$ is not saturated; (ii) the second case is where the reactive control structure is defined by the secondary loop only, that is, $u_1(t)$ is saturated and the controller is defined by the combination $C(s) = C_1(s)C_2(s)$; and (iii) the third control condition appears when including preventive protection, i.e. $\eta > 0$ while $u_1(t)$ is not saturated.

The above decomposition of the problem indicates that $C_1(s)$ must be adjusted for high quality control when the subsystem $Gp_1(s)$ handles the regulation, i.e. $u_1(t) \le \bar{u}_1\ \forall t$. This is essentially the traditional design and tuning problem for a single feedback loop. When $u_1(t) > \bar{u}_1$, the subsystem $Gp_2(s)$ must provide the complementary effect on the controlled variable, which means that $C_2(s)$ must be combined with $C_1(s)$ such to obtain the best possible performance. Finally, the case $\eta > 0$ combines the two previous loops and requires an additional stability analysis. Useful guidelines for designing and tuning controllers $C_1(s)$ and $C_2(s)$ are presented in following subsections.

2.3.1. *Cancellation design*

Recognizing that realizable controllers often have a lead-lag type of transfer function, selecting the combined controller $C(s)$ as being of equal or higher order than $C_1(s)$ will always yield a realizable $C_2(s)$. Hence, standard design and adjustment procedures may be followed to conveniently define $C_1(s)$ and $C(s)$ for controlling $Gp_1(s)$ and $Gp_2(s)$, respectively, as if they were not related to each other. Then, the second controller $C_2(s)$ is determined by

$$C_2(s) = C(s)C_1^{-1}(s) \tag{2}$$

The following few hypothesis and practical reasons give additional guidelines to assigning the controller modes:

1) A single integral-mode is necessary only in $C_1(s)$, because offset elimination is desired under all working conditions, and this controller is always active. Furthermore, $C_2(s)$ must not have integral mode since $f(u_1) \geq 0 \, \forall t$, and consequently u_2 would not go back to be null once the protection is not longer necessary.
2) The control system structure assumes that $Gp_1(s)$ is faster and has a smaller time-delay than $Gp_2(s)$; this could be a main argument for selecting $u_1(s)$ as the preferred or primary manipulated variable. This also suggests that if a derivative term is desired, it should be included in $C_2(s)$ so that it actuates on the slower plant dynamics.

These statements lead to the following possible controllers featuring traditional controller modes:

- Combined PID controller from PI and PD algorithms. This is a quite frequent case, where $C_1(s)$ is the PI controller

$$C_1(s) = K_{C_1}\left(1 + \frac{1}{T_{I_1}s}\right) \tag{3}$$

and $C_2(s)$ is the ideal PD controller

$$C_2(s) = K_{C_2}(1 + T_{D_2}s) \tag{4}$$

Thus, the combination $C(s) = C_1(s)C_2(s)$ results in the ideal PID

$$C(s) = K_C\left(1 + \frac{1}{T_I s} + T_D s\right) \tag{5}$$

with parameters

$$K_C = K_{C_1}K_{C_2}\left(1 + \frac{T_{D_2}}{T_{I_1}}\right) \tag{6}$$

$$T_I = T_{I_1} + T_{D_2} \tag{7}$$

$$T_D = \frac{T_{I_1}T_{D_2}}{T_{I_1} + T_{D_2}} \tag{8}$$

A method based on IMC parametrization for tuning this combined system is discussed in Giovanini and Marchetti (2000).

- Combined PI controller from I and PD controllers. This combination is particularly useful in HENs when the primary controller $C_1(s)$ is a pure integral mode as suggested by Rotea and Marchetti (1997) for bypass temperature control. This is a case in which $C_1(s)$ is realizable but does not have the typical lead-lag form, i.e.

$$C_1(s) = \frac{1}{T_{I_1}s} \tag{9}$$

This controller is adjusted using the tuning formula $T_{I1} = 1.353K_1T_{\mathrm{d}}$, where T_{I1} is the integral constant, T_{d} stands for the time-delay due to the distance from the mixing point to the temperature sensor, and K_1 is the initial process gain. If the PI controller

$$C(s) = K_C\left(1 + \frac{1}{T_I s}\right) \tag{10}$$

is adopted as a combined controller in a flexible-structure loop, then using the cancellation approach in Eq. (2), and from Eqs. (9) and (10), it follows that $C_2(s)$ is an ideal PD controller. Once the combined controller $C(s)$ is tuned, the parameters of the secondary controller are determined from $T_{D2} = T_I$, and $K_{C2} = K_C T_{I1}/T_{D2}$.

- Combined P, PI or PID where the main controller is a P, PI or PID and de auxiliary controller is a P only.

2.3.2. *Stability analysis*

The general stability analysis for the flexible-structure control system described above requires the analysis of every single or combined control loop in the system. When the manipulated variable u_1 is not saturated the characteristic equation for the primary control loop includes only $Gp_1(s)$ and $C_1(s)$, and the stability condition may be written as

$$1 + Gp_1(s)C_1(s) \neq 0 \quad \forall s \in C^+ \tag{11}$$

where C^+ stands for the closed right-half complex plane. The second relevant stability condition is for the secondary loop which adjusts the manipulated variable u_2 when u_1 is saturated, namely

$$1 + Gp_2(s)C_2(s)C_1(s) \neq 0 \quad \forall s \in C^+ \tag{12}$$

Finally, for the intermediate case when $\eta > 0$ and $u_1(t) < \bar{u}_1$, two control paths coexist simultaneously: one through u_1 and the other through u_2. Then, the stability condition is given by the inequality

$$1 + Gp_1(s)C_1(s) + \eta Gp_2(s)C_2(s)C_1(s) \neq 0 \quad \forall s \in C^+ \tag{13}$$

The first two conditions can be satisfied sequentially, namely, Eq. (11) must hold adjusting controller $C_1(s)$, and Eq. (12) while adjusting controller $C_2(s)$. Hence, the stability problem reduces to determining the range of values $0 \leq \eta < \eta_{\max}$ satisfying condition (13). This task can be simply accomplished after notice that Eq. (13) can be rewritten as

$$1 + \eta G(s) = 0 \tag{14}$$

where

$$G(s) = \frac{Gp_2(s)C_2(s)C_1(s)}{1 + Gp_1(s)C_1(s)} \tag{15}$$

Thus, the maximum value for η is easily determined as the reciprocal of the magnitude $|G(s)|$ at the phase crossover frequency ω_o, namely

$$\eta_{\max} = \frac{1}{|G(j\omega_o)|}. \tag{16}$$

3. Control loops in heat exchanger networks

3.1. Defining the main control loops

The control performance in HENs mainly depends on the kind of manipulated variables associated with the feedback loops. Hence, if the goal is to attain the best possible control quality for the largest number of process streams, Aguilera and Marchetti (1998) suggest defining a control configuration by selecting manipulated variables according to the performance they can deliver: (1) direct bypass on controlled streams; (2) service flow rates—typically final equipment on process streams; (3) non-direct acting bypasses on internal exchangers; and (4) stream split ratios. The achievable loop-control performance for this sequence ranges from near-perfect control for the first one (Rotea and Marchetti, 1997) to sluggish and interacting for the last one.

Configuring control loops for flexible HENs could be more or less difficult depending on the network structure, and might require iterative analysis until all the relevant operating conditions are properly addressed. In the case of FSC, the idea is to reach good control performance for the given network without reducing operability, while preserving heat integration; other considerations come in second place after one knows how much control quality is sacrificed and on which control targets. Once the main regulating loops are defined, the remaining manipulated variables become secondary manipulated variables by default.

3.2. Differences between protecting and optimizing actions

A first step in analyzing the effect of FSC on the optimal operation is to determine the number of degrees of freedom available. Given an HEN, the degrees of freedom (or the number of secondary variables available) for protecting the manipulated variables can be computed from

$$f_\mathrm{p} = (n_\mathrm{e} + s_\mathrm{e} + n_\mathrm{split}) - (n_\mathrm{hot} + n_\mathrm{cold}) \tag{17}$$

where n_e is the number of heat exchangers, s_e is the number of service equipment, n_split is the number of process-stream splits, n_hot is the number of hot-process streams with temperature targets, and n_cold is the number of cold-process streams with temperature targets. According to Aguilera and Marchetti (1998), these f_p variables might affect optimization in the sense of obtaining maximum heat integration. However, the structural flexibility for optimization should be computed by

$$f_\mathrm{op} = (n^\mathrm{o} + s_\mathrm{e}) - 1 \tag{18}$$

where n^o stands for the number of non-controlled process streams. The meaning of f_op is extensively discussed in the last mentioned reference; however, it seems important to recall the following points:

1) $f_\mathrm{op} < 0$, means that there is no compatibility between the proposed network structure and the number of desired targets for the regulating system. The system is not controllable.
2) $f_\mathrm{op} = 0$, means that there is one outlet-free stream—utility or process stream—which allows the operation of the network. The control loop using this outlet-free stream as manipulated variable cannot be protected from saturation. Once the HEN regulating system achieves the control targets, the extent of energy integration is completely determined. This kind of network might have flexibility to vary excess bypasses or split ratios within limited ranges while satisfying all the regulating targets, but the extent of energy integration cannot be improved. These multiple but equivalent operating points imply a flexibility that does not allow optimization, but that might nevertheless help to protect manipulated bypasses from saturation.

3) $f_{\mathrm{op}} > 0$, means that there is more than one stream path to release energy disturbances. The network can have many steady-states with different utility loads—for the same targets and input conditions—and consequently, optimization would make sense. However, three sub cases must be noted:
   a) All the stream paths allowing the release of energy disturbances are associated to cooling operations only, and occasionally there are hot process streams without temperature targets. If the operation of these coolers or free streams has the same cost, the added flexibility helps for control protection only, but not for optimization.
   b) All the stream paths allowing to release energy disturbances are associated to heating operations only, and occasionally there are cold process streams without temperature targets. Similarly to the previous case (a), optimization would be possible if the heating utilities have different costs, or if a free-outlet cold process stream is available, or both.
   c) The network has heating and cooling utilities available, and occasionally, process streams without temperature targets. This is a case where FSC maintains regulation, sometimes following the optimal condition without back-off, but sometimes moving away from the optimal operating point.

3.3. General guidelines to define FSC systems

Given an HEN, the followings steps help to proceed in an orderly manner towards the definition of the feedback loops for the regulating system:

1) Compute the overall number of independent outlet-free streams f_{op} to find if the operation of the HEN admits optimization, and if the HEN is structurally controllable.
2) Compute the overall number of free variables f_{p} that may be used to protect manipulated variables from saturation.
3) Select the primary manipulated variables following, for instance, the guidelines given by Aguilera and Marchetti (1998).
4) Determine which are the manipulated variables available for secondary or auxiliary control actions: typically stream splits, temporary utilities and process-process exchangers far from final temperature targets.
5) If necessary, define preliminary values for parameters η and κ to protect the regulating system from the saturation of primary manipulated variables.
6) Review the adjustment and the whole configuration making sure the operability in the desired space.

4. Application of FSC to an example

An analysis of the alternatives for association among two or more manipulated variables is quite important when defining an FSC for an HEN. In fact, more than one pattern similar to those shown in Figs. 2–5 may be used simultaneously in the same HEN. Since every extreme operating condition might require a different protection scheme, the final configuration is defined analyzing all critical operating points where a control saturation might happen.

The example network used in this work have been previously proposed as a benchmark by Aguilera and Marchetti (1998) (see Fig. 7). These authors simulated the use a hierarchical two-level control approach to optimally operate and control the network. The entire control structure consists of a high-level supervisory system that optimizes the operation, and a regulation and tracking control system at the lower level. The reasons to adopt this network as a benchmark are twofold: (i) it has constraints on manipulated variables; and (ii) the dynamic performance and the level of energy integration obtained using FSC can be compared with results obtained using more elaborated on-line optimizing approach. The nominal stream conditions for this network are given in Table 1, and the heat-exchanger areas are in Table 2.

A justification for the bypass configuration exhibited in Figure (7) is outside the scope of this article. A detailed discussion is given in Aguilera and Marchetti (1998), where the configuration is identified as design B. The focus here is on those manipulated variables that hit limit constraints when the system follows a sequence of setpoint changes, and when it must reject a sequence of load disturbances. The flexible-structure approach and the supervisory method are tested under the same conditions to ensure a meaningful comparison.

When the on-line optimizing method was used in this network, Aguilera and Marchetti (1998) adopted bounds of 0.1 and 0.9 for protecting bypasses from saturation, and chose $\alpha_{S_1} = 15$ kW (5% of the nominal duty) and $\beta_{S_1} = 0.95$ for protecting the control loop associated with the cooler S_1 (see Appendix A). Table 3 shows nonlinear programming results for different steady operating conditions under supervisory control. The first column identifies the nominal steady-state and two sequences of changes: (1) a sequence of step disturbances on inlet stream temperatures; (2) a sequence of step changes on temperature control targets. This table shows that the manipulated variables that reach the limiting values after set point changes and load disturbances are: (i) w_{s1}, the service stream flowrate in the cooler S_1 ($q_{S1} = 15$ kW); and (ii) x_3, the bypass to the heat exchanger I_2 and the service equipment S_2 ($x_3 = 0.1$). The frequent saturation of bypass x_3 is a consequence of the double bypass to the heat exchanger

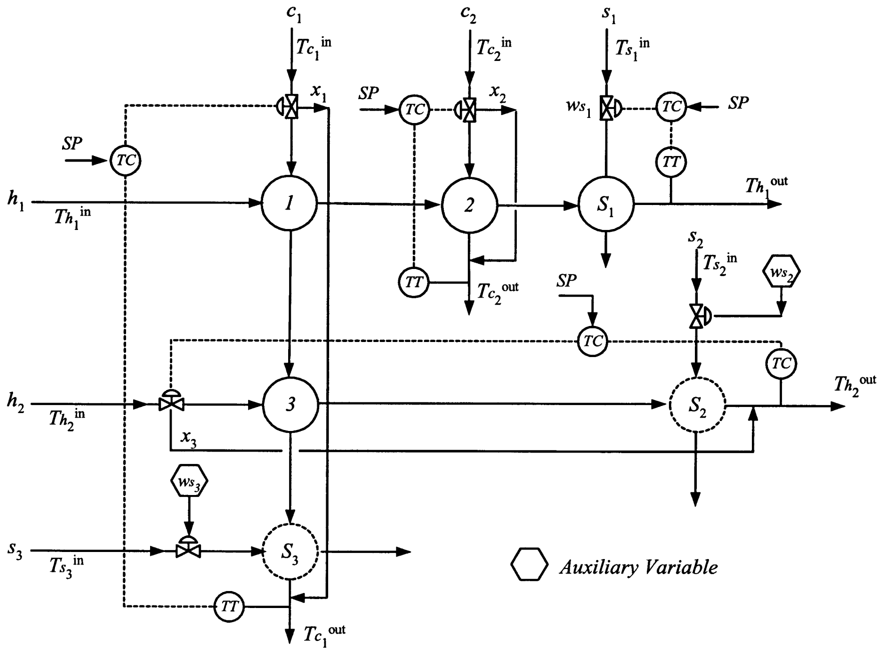

Fig. 7. HEN used for testing and comparing the FSC strategy.

Table 1
Stream conditions for the nominal operation point

Stream	T^{in} (°C)	T^{out} (°C)	$w^o c$ (kW/°C)
h_1	90	40	50
h_2	130	100	20
c_1	30	80	40
c_2	20	40	40
s_1	15	–	35 (max)
s_2	30	–	30 (max)
s_3	200	–	10 (max)

Table 2
Effective heat transfer areas (UA) for the heat exchangers in Fig. 7

Equipment	1	2	3	S_1	S_2	S_3
UA (kW/°C)	80	50	20	30	20	10

I_3; this means that though direct bypass gives good control performance for temperature T_{h2}, it also reduces the operating space, enhancing the importance of the constrained problem.

Defining FSC loops for multivariable processes has two basic aspects. The first one involves the selection of main or primary manipulated variables for each controlled output, i.e. it means solving the variable-pairing problem. The second aspect consists of defining secondary or auxiliary variables for those loops that require them. If the criteria given by Aguilera and Marchetti (1998) are applied to the benchmark HEN, the first aspect is readily addressed (the loops are those shown in Fig. 7). The functions f_{op} and f_p determine that there are 2 degrees of freedom for optimizing and protecting the control system from saturation; these are the variables used as optimizing commands, namely, the utility flow

Table 3
Optimum steady-states using a supervisory system

Case	q_1 (kW)	q_2 (kW)	q_3 (kW)	q_{S1} (kW)	q_{S2} (kW)	q_{S3} (kW)	x_1	x_3	J_{1+2+3} (kW)
Nominal	1467	800	533	233	67.2	0	0.288	0.100	2800
Loads									
$T_{h1}^{in} = 80$ °C	1185	800	596.5	15	3.5	218.5	0.272	0.100	2581.5
$T_{h2}^{in} = 140$ °C	1185	800	697	15	103	118	0.272	0.100	2682
$T_{c1}^{in} = 40$ °C	930	800	670	270	130	0	0.297	0.100	2400
Setpoints									
$T_{c1}^{out} = 70$ °C	1172	800	428	528	172	0	0.464	0.124	2400
$T_{c2}^{out} = 45$ °C	1169.5	1000	430.5	330.5	169.5	0	0.464	0.100	2600
$T_{h2}^{out} = 90$ °C	1169.5	1000	430.5	330.5	369.5	0	0.464	0.100	2600

rates w_{s2} and w_{s3}. These same variables become secondary control options for the FSC approach.

A complementary or auxiliary control system must be defined now for those loops whose manipulated variables might saturate. The following statements provide simple rules to select the associated variables in an HEN, in a one-at-a-time fashion:

1) Determine the energy disturbance that might lead to the saturation of main manipulated variables, and the kind of action that would be required to compensate the effect in each case.
2) Select as secondary manipulated variable, the auxiliary variable that is closest to the controlled stream being consistent with the required type of action. It is important to note that auxiliary variables must provide—directly or indirectly—a way out for the disturbance generating the problem.
3) Do not use a main or primary control variable as a secondary variable to protect another feedback loop. However, under preventive protection, the same auxiliary variable could occasionally provide assistance to more than one main control loop.

Analyzing the results in Table 3 it is concluded that the lower bounds for x_3 and w_{s1} must be protected. For example, consider the bypass controlling T_{h2}, which might saturate at the lower bound $x_3 = 0$. If x_3 moves towards zero it means that a hot perturbation is unfavorably affecting the loop, and the disturbance has to be addressed somewhere else. The appropriate sink for a hot disturbance is a free-outlet process stream or an auxiliary cooler. Since the first alternative is not available, the cooler flow rate w_{s2} becomes the secondary control variable. Notice that the resulting process subsystem is similar to that shown in Fig. 3.

The utility flow rate in the service equipment S_1 might also reach the lower-bound constraint. If this happens to a cooler, it means that the network has sustained a change equivalent to a cold perturbation. Since there are no free-of-target process streams, the only sink available for the cold disturbance is the heater S_3. Unfortunately, the service S_3 is far from S_1, but there is no other choice available in this network.

On the contrary, if an important heat disturbance drives the cooling service S_1 to its maximum capacity, part of the compensating duty must be addressed to S_2 to maintain closed-loop control of T_{h1}. In other words, the control system must deliver a convenient distribution of the overall cooling task between both cooling equipment. Note that the bypass x_3 would take full control of T_{h2} if the duty of S_2 is increased.

Simulation studies similar to those presented in the next section also illustrate the convenience of protecting the lower bound of x_2. This generates an additional demand for the heater S_3 partially compensating for the existing lag between the heater S_3 and equipment I_2 and S_1.

4.1. Simulation results

An interactive dynamic simulator of heat exchanger networks developed in INTEC has been used to test the above example. The simulator is based on a nonlinear model of shell-and-tubes heat exchangers previously reported by Correa and Marchetti (1987).

The numerical experience reported here repeats the disturbance and setpoint change sequence used for testing the optimizing and control system presented by Aguilera and Marchetti (1998). In this case, the low-level FSC system comprises the control loops in Figure (7), plus a complementary control system which accommodates the auxiliary duties of services S_2 and S_3. This complementary system is defined following the guidelines and comments in the previous subsection, and adopts the design and tuning procedure discussed in Section 1. Table 4 lists the additional control modes included for each case needing protection, and the type of protection provided during the simulations.

Table 5 shows the steady-state network conditions reached using the FSC system. These data must be compared to those given in Table 3; the first row, for instance, indicates heat duties reached for the nominal operating point in Table 1. A key difference between the results reported in Tables 3 and 5 is the elimination of the constraint $x_3 \geq 0.1$ included by the supervisory scheme to control T_{h2}. Since the FSC system used here gives additional support to the regulation of T_{h2} through the service flowrate w_{s2}, such limiting value for the bypass ratio is not longer necessary. Note that the bypass x_3 closes completely now, and consequently, the heat duty of service S_2 is lower than that reported in Table 3. The variable x_3 reaches zero as a consequence of the fact that the FSC system defines only a reactive protection for this loop. This can be confirmed by observing that x_3 is null only when q_{S2} is not null, and viceversa. From the energy point of view, it should be noted that both nominal operating points use only coolers, i.e. the network is under these conditions in case a) since $f_{\mathrm{op}} > 0$, where changes in heat integration should not be expected. The same explanation is also adequate for the last four stationary conditions listed in the tables, where FSC delivers the same heat integration that the optimizer, essentially because w_{s3} is not required for protection and the balance between w_{s1} and w_{s2} compensates for the elimination of back-off from $x_3 = 0$.

Figs. 8–10 show the dynamic responses obtained using FSC on the HEN of Fig. 7 for the following scenario: after running at the nominal operating point, T_{h1}^{in} changes from 90 to 80 °C; 10 min later T_{h2}^{in} goes from 130 to 140 °C, and after another 10 min T_{c1}^{in}

Table 4
Auxiliary control system for FSC

Main control variable	Modes in $C_1(s)$	Auxiliary variable	Modes in $C_2(s)$	Kind of protection	Bound $\bar{u}_1$	Preventive action at κ	Intensity η
x_3	I	w_{S2}	PD	Reactive	0.0	0.0	0.0
w_{S1}	PI	w_{S3}	P	Preventive	0.0	0.2	1.0
X_2	I	w_{S3}	P	Preventive	0.0	0.2	1.0

changes from 30 to 40 °C. The capability of FSC for disturbance rejection can be evaluated by inspection of Fig. 8. The worse performance is observed during the time period between the first and second load changes, most notably on temperature T_{h1}^{out}. The reasons for this behavior can be found by observing the manipulated variables.

The first fact to be noted is that under nominal steady-state conditions, the bypass x_3 is completely closed and T_{h2}^{out} is controlled by the flowrate service w_{s2}. Observe also that S_3 is inactive since no heating service is necessary at this point. After the first load change occurs, both control variables w_{s1} and x_2 fall rapidly. When w_{s1} reaches 0.2, the system activates the preventive protection through the heater flowrate w_{s3}. The dynamic reaction of the heater to the cool disturbance is also stimulated by the bypass x_2 when it falls below 0.2. After the initial effect is compensated, the control of T_{c2}^{out} through x_2—which never saturates—remains under preventive protection, while w_{s3} takes complete control of T_{h1}^{out} through the reactive protection. Furthermore, Fig. 10 shows that the cool perturbation also affects the process stream h_2, where the cooler S_2 is effectively taken out of operation by the bypass x_3. Note that the stationary condition obtained using FSC after the first load change yields better heat integration than the optimizer proposed by Aguilera and Marchetti (1998). This improvement is due to the elimination of back-off from $w_{s1} = 0$ and $x_3 = 0$. The control of T_{h1}^{out} using w_{s3} however, shows a lower performance.

The ensuing pair of load changes are heat perturbations featuring manipulated movements in the opposite sense to those indicated above. Though the input change in h_2 allows returning the control of T_{h1}^{out} from w_{s3} to w_{s1}, the heater keeps working under a preventive condition. Note that the heater closes completely when the cool stream c_1 rises its inlet temperature. The heat integration after the second load change appears to be quite similar for both cases being analyzed; however, it is important to note that FSC holds preventive protection under this condition, and this depends on parameters κ and η The figures for a completely reactive scheme, though poorly controlled, would have $q_{S1} = 0$, $q_{S2} = 73.3$ kW, $q_{S3} = 73.3$ kW, and $J_{1+2+3} = 2726.7$ kW.

Now consider the sequence of set point changes is as follows: first the target for T_{c1}^{out} changes from 80 to 70 °C; 10 min later the set point for T_{c2}^{out} changes from 40 to 45 °C, and after another 10 min T_{h2}^{out} is taken to 90 from 100 °C. As for the case of load changes, the control performance can be evaluated observing the temperature evolutions in Fig. 11; however, the actions of the FSC system is better understood by inspection of the control variables shown in Fig. 12. A quite interesting fact to observe is that though the control design for T_{h2}^{out} was originally thought as commanded primarily by the bypass x_3 and using w_{s2} as auxiliary variable, in these numerical experiences these variables appear to have switched roles without affecting the performance significantly.

Table 5
Steady-states obtained using FSC

Case	q_1 (kW)	q_2 (kW)	q_3 (kW)	q_{S1} (kW)	q_{S2} (kW)	q_{S3} (kW)	x_1	x_3	J_{1+2+3} (kW)
Nominal	1455	800	545	245	55	0	0.238	0.0	2800
Loads									
$T_{h1}^{\text{in}} = 80$ °C	1200	800	600	0	0	200	0.260	0.094	2600
$T_{h2}^{\text{in}} = 140$ °C	1170	800	710	30	90	120	0.286	0.0	2680
$T_{c1}^{\text{in}} = 40$ °C	1160	800	683	283	117	0	0.311	0.0	2400
Setpoints									
$T_{c1}^{\text{out}} = 70$ °C	1160	800	440	540	160	0	0.468	0.0	2400
$T_{c2}^{\text{out}} = 45$ °C	1160	1000	440	304	160	0	0.468	0.0	2600
$T_{h2}^{\text{out}} = 90$ °C	1160	1000	440	304	360	0	0.468	0.0	2600

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Computer & Chemical Engineering, Vol. 27, No. 8–9, pp. 1129–1142, 2003.

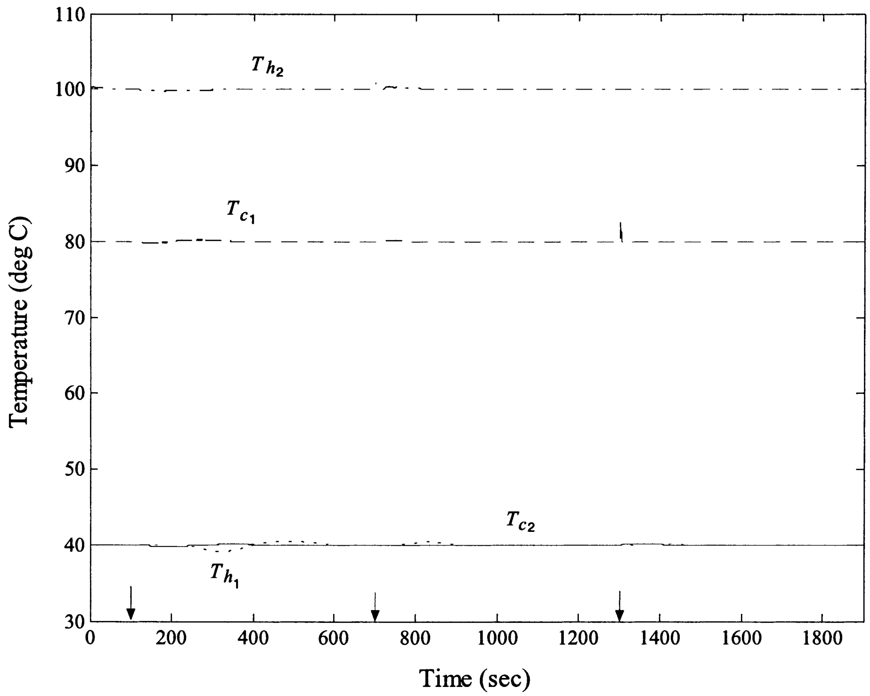

Fig. 8. Load disturbance rejection achieved by the FSC system.

5. Conclusions

This article shows that the use of low-level fexible-structure control systems is an efficient alternative for controlling heat exchanger networks. An appropriately designed FSC system is able to keep closed-loop control of heat exchanger networks while maintaining operation near optimal conditions under the presence of manipulated variable constraints. Since this strategy provides capability for switching from one closed-loop structure to another when a manipulated variable hits a constraint, it frequently allows regulation without back-off from the optimal conditions or alternatively, it realizes a reasonable trade-off with control performance.

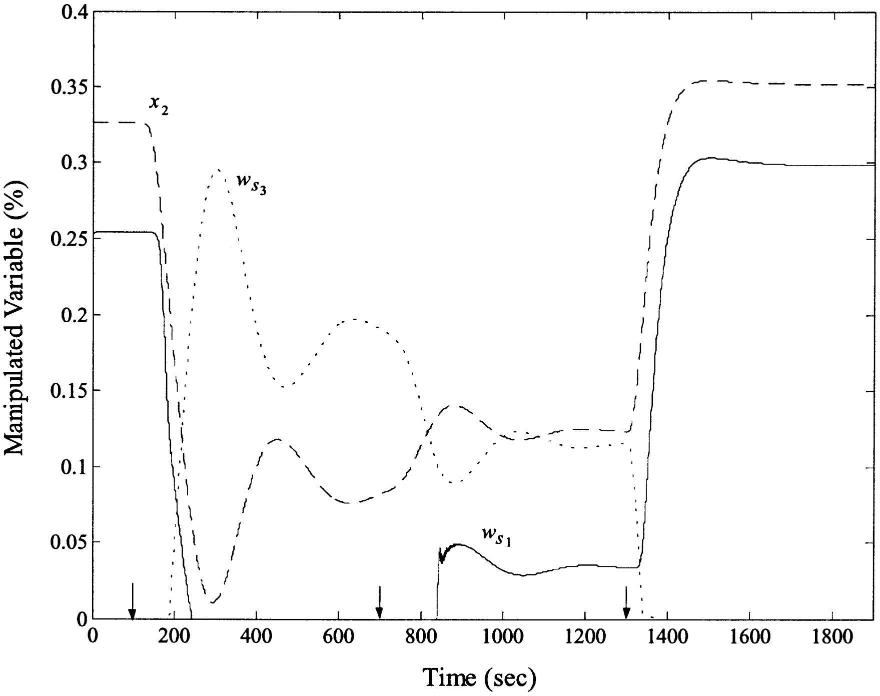

Fig. 9. Combined control action of the cooler S_1 and the heater S_3.

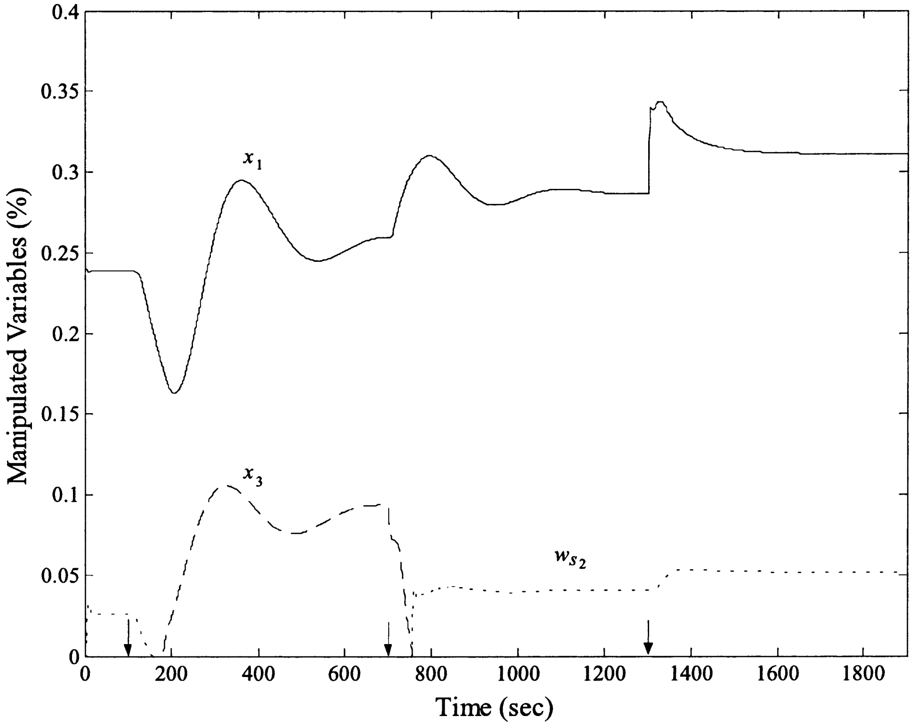

Fig. 10. Combined control action of the bypass x_3 and the cooler S_2.

Dynamic simulation studies show that FSC can deliver reasonable good control performance. The level of heat integration reachable with this new approach compares quite well with available results obtained using a more involved optimization strategy. The near-optimizing nature of the resulting control system is obtained by involving the closest auxiliary variable that provides the adequate action to relief the disturbance

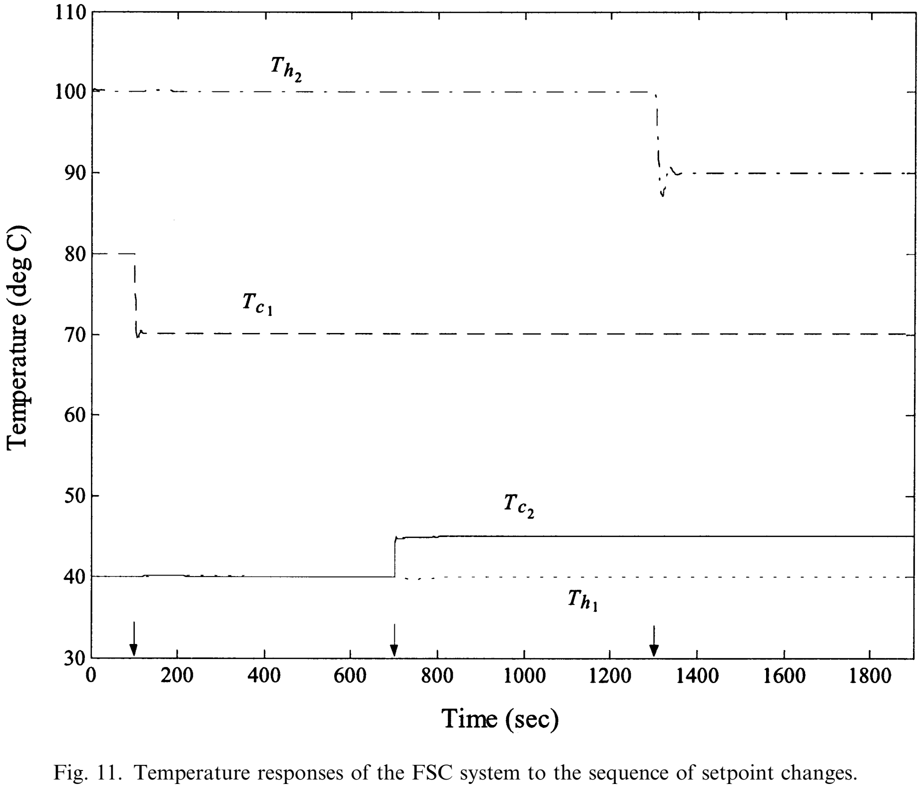

Fig. 11. Temperature responses of the FSC system to the sequence of setpoint changes.

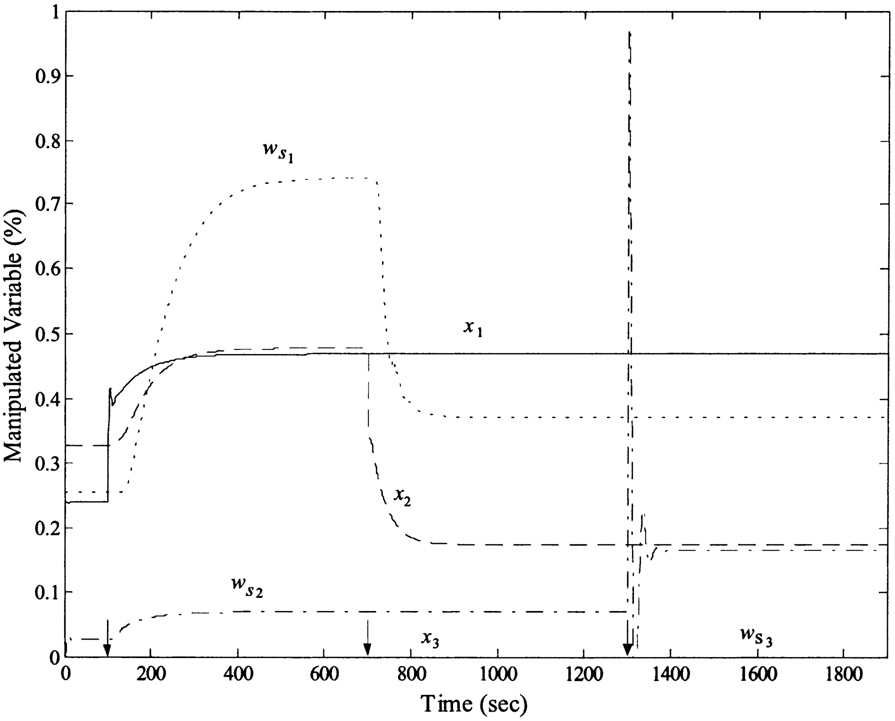

Fig. 12. Manipulated variable movements during the setpoint sequence.

that is creating the problem. However, the success for tracking the optimal operating point depends very much on each particular HEN and on the actual operating condition at a given time instant. Hence, for cases with enough structural flexibility, the combination of FSC with a supervisory control scheme is particularly beneficial for two reasons: (i) FSC simplifies the on-line optimization task since the optimizer must not prevent frequent control saturations; and (ii) FSC avoids back-off from optimal operating points.

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Appendix A: Heat-exchanger constraints

The amount of energy that the cold stream takes when heated from T_j^0 to T_i^0, can be written as

$$L = w_j c_j (T_i^0 - T_j^0) \tag{19}$$

where i stands for hot stream, j stands for cold stream, and the superscript ‘0’ stands for heat-exchanger inlet conditions. Let the superscript ‘o’ also denote a fully-open control valve or fully-closed bypass; then the operating interval of a single heat exchanger, where a total flow rate or a bypass ratio is manipulated, can be written in terms of the stream-match available energy L^{o} given by Eq. (19) and the heat exchanger efficiency e^{o}, as follows:

$$0 \leq q \leq e^{\mathrm{o}} L^{\mathrm{o}} \tag{20}$$

Here, the extremes $q = 0$ and $q = e^{\mathrm{o}} L^{\mathrm{o}}$ imply fully-closed and fully-open control valve, or fully-open and fully-closed bypass, respectively. Any other intermediate condition represents an operating point where the control valve, or the bypass, is partially open.

In case that an unit used for regulation is indirectly driven out of operation by the optimizer, a protection must be introduced by modifying the non negativity condition in Eq. (20), as follows:

$$-q_k \leq -\alpha_k, \quad k \in \{1, n_{\mathrm{e}} + s_{\mathrm{e}}\} \tag{21}$$

where α_k is the resigned amount of energy determining how close to saturation the manipulated variable can reach in the unit k. The constraints might have to be also modified for under-designed units to appropriately define the maximum heat transfer capacity, for instance

$$q_k \leq \beta_k e_k^{\mathrm{o}} L_k^{\mathrm{o}}, \quad k \in \{1, n_{\mathrm{e}} + s_{\mathrm{e}}\} \tag{22}$$

where β_k is a fraction close to 1, reducing the amount of energy that can be transferred in the unit k. Further details can be found in Aguilera and Marchetti (1998).

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