Chapter 3

Control of Heat Exchanger Networks - I: Dynamic Behaviour and Control Limitations

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Abstract

The dynamic behaviour of heat exchanger networks with emphasis on phenomena that may cause control problems is studied. Specifically, it is explained how structural singularities, right-half-plane zeros, time delays, input constraints and interactions may arise. Structural singularity is due to insufficient number of downstream paths from the inputs to the outputs. Right-half-plane zero in heat exchanger networks are caused by competing effects from two parallel downstream paths from an input to an output, and may occur in networks with split streams or networks where the heat load on inner matches are used as manipulated inputs. Considerable time delays mainly occur for networks where the temperature effect must traverse a heat exchanger from inlet temperature to outlet temperature on the same side. Input constraints and interactions may become important for networks where both outlet temperatures of one heat exchanger are controlled outputs. These insights may be used both during network design and control design to improve the controllability of the resulting system.

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3.1 Introduction

The objective of this paper is to identify and explain important dynamic characteristics of HENs, in particular behaviour or phenomena that may limit the controllability of the plant. The term controllability in this context has the meaning *inherent control characteristics* or *achievable control performance* irrespective of the controller. Furthermore, a simple decentralized controller is preferred since it will make the plant easier to operate. Thus, we will also discuss dynamic characteristics that may make it necessary to use an advanced controller.

Propagation of disturbances and input manipulations and the following control limitations will be discussed:

- structural singularities
- right half plane zeros
- time delays
- input constraints
- interactions
- nonlinearities

Inputs, i.e., disturbances and manipulated variables, in HENs only affect the outputs if there is a "downstream path" (Linnhoff and Kotjabasakis, 1986) between the input and the output. Absence of a downstream path yields structural singularity. For disturbances structural singularity is desirable (e.g., Georgiou and Floudas, 1990), whereas for manipulated inputs it must be avoided as the plant becomes uncontrollable. In this paper we consider structural singularities, explain their origins and divide them into categories.

A right half plane (RHP) transmission zero represents a fundamental limitation of the achievable control performance (Rosenbrock, 1970; Morari, 1983). Plants with RHP zeros may have inverse responses and fast and efficient control is impossible. Thus, identification of possible RHP-zeros are very important when comparing alternative designs. The main contribution of this paper is to explain how RHP-zeros and inverse responses may occur in HENs.

Time delays represent another fundamental limitation of the achievable control performance (Ziegler and Nichols, 1943; Rosenbrock, 1970). For HENs the time delay is due to mass and energy holdup in the heat exchangers and mass holdup in the connecting pipes. Holt and Morari (1985) show that controllability of some HEN can be improved by *increasing* the time delay between the exchangers. This may at first seem counterintuitive, but some thought reveals that it is generally an advantage to increase delay on off-diagonal elements in multivariable systems as it reduces the interaction.

Adequate disturbance rejection is important both for flexibility and controllability. Disturbances should have small effects and the manipulated inputs large and fast effects on the outputs, otherwise problems with input constraints will occur. Input constraints are difficult to address with a phenomenon approach because they strongly depend on scaling.

The relative gain array, RGA, (Bristol, 1966, 1978) and some of the related controllability measures (Hovd and Skogestad, 1993) are used for evaluating interactions between control loops. We explain that interactions will always be present in HENs, but that the interactions may be small or only one-way. When both outputs of one heat exchanger are controlled outputs, there will usually be strong interaction between the control loops. However, control problems due to large RGA elements (Skogestad and Morari, 1987) will usually not occur.

Heat exchangers have been considered to be extremely nonlinear (Shinskey, 1979) and control of single heat exchangers are sometimes used in articles on nonlinear control (e.g., Alsop and Edgar, 1989; Khambanonda *et al.*, 1991). Both thermal effectiveness and heat transfer coefficients depend on the flowrate, and this is the main cause for the nonlinearity. However, results from bypass control of single heat exchangers in Mathisen *et al.* (1993)* indicate that the nonlinearity is usually of secondary importance, and we will not consider any further in this paper.

To study the dynamic behaviour of HENs, we use the dynamic multicell model described in Mathisen *et al.* (1993).

3.2 Propagation of disturbances and manipulations

3.2.1 Steady-state behaviour of heat exchangers

The steady-state energy balance for heat exchangers is

$$w^h(T_i^h - T_o^h) = w^c(T_o^c - T_i^c) = UA\Delta T_{hx} \tag{3.1}$$

where T is temperature, w heat capacity flowrate, superscript h means hot side, c cold side; subscript i inlet, o outlet; U overall heat transfer coefficient and A is the exchanger area. The overall temperature driving force of the heat exchanger, ΔT_{hx}, depends on the flow configuration.

We now introduce the thermal effectiveness for the hot and the cold side:

$$P^h = (T_i^h - T_o^h)/(T_i^h - T_i^c) \tag{3.2}$$

$$P^c = (T_o^c - T_i^c)/(T_i^h - T_i^c) \tag{3.3}$$

and it is clear that thermal effectiveness is bounded between zero and unity.

Then the steady-state equation for heat exchangers may be expressed as (Appendix 1 of Ch. 2; Kern, 1950):

$$\begin{bmatrix} T_o^h \\ T_o^c \end{bmatrix} = \begin{bmatrix} 1-P^h & P^h \\ P^c & 1-P^c \end{bmatrix} \begin{bmatrix} T_i^h \\ T_i^c \end{bmatrix} \tag{3.4}$$

*corresponds to chapter two of this thesis

Importantly, P^h is a function of heat capacity flowrate ratio $R^h = w^h/w^c$, the number of transfer units $N^h_{TU} = UA/w^h$, and flow configuration only. Moreover, there is a simple relation between the thermal effectiveness of the cold and the hot side: $P^c = R^h P^h$.

Countercurrent flow configuration yields the best thermal effectiveness, and it may be expressed as:

$$P^h = \frac{1 - \exp(-N^h_{tu}(1 - R^h))}{1 - R^h \exp(-N^h_{tu}(1 - R^h))} \tag{3.5}$$

Expressions for other flow configurations are given by Heggs (1985) and Martin (1990).

3.2.2 Transfer functions

For control, relations between inputs and outputs may be conveniently expressed through deviation variables and transfer functions. With a single heat exchanger, the outputs are the outlet temperatures. We denote the transfer function from inlet temperatures G_T, from heat capacity flowrates as G_w, and from manipulated inputs (usually bypass fractions) as G.

3.2.3 Steady-state effects of temperature variations

Since the thermal effectiveness is independent of temperature, Eq. 3.4 shows that temperature variations propagate *linearly* in heat exchangers. Usually inlet temperatures are disturbances rather than manipulators, but temperatures in HENs are often manipulated indirectly by changing the heat load on an upstream exchanger.

Single heat exchangers

The steady-state transfer function from inlet to outlet temperatures of a single heat exchangers (G_T at zero frequency) is from Eq. 3.4 simply:

$$G_T(0) = \begin{bmatrix} 1 - P^h & P^h \\ P^c & 1 - P^c \end{bmatrix} \tag{3.6}$$

In Fig. 3.1 it is illustrated how the four extreme combinations of thermal effectiveness affect propagation of temperature variations. Note that an inlet temperature variation may have a large effect on both, one or none of the outlet temperatures depending on heat exchanger parameters.

Multivariable singularity

The transfer matrix G_T looses rank if:

$$det(G_T) = 0 \tag{3.7}$$

At steady state this is fulfilled if and only if

$$P^h = 1 - P^c \Leftrightarrow P^h = \frac{1}{1 + R^h} \tag{3.8}$$

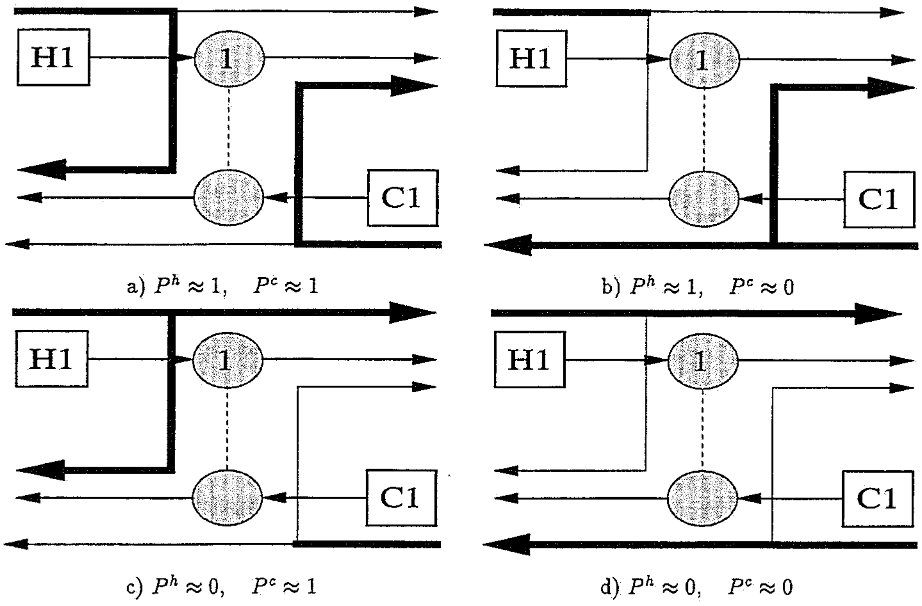


Figure 3.1: Propagation of temperature disturbances across heat exchanger with high and low hot and cold thermal effectiveness

Note that this condition may easily be fulfilled during practical operation. This multivariable singularity is surprisingly little discussed in the literature. Reimann (1986, pp. 53-54) points out that the relative gain array (RGA) at steady-state changes sign, and that the appropriate pairing depends on the operating point. However, more importantly, at the point of singularity given by Eq. 3.8 it is impossible to adjust the two outlet temperatures independently using the inlet temperatures. Moreover, close to this point, independent adjustment will require very large changes in the inlet temperatures, which will be impossible in practice. It may be argued that the singularity is not important since inlet temperatures usually cannot be manipulated directly. However, adjusting upstream bypass flows yield temperature changes, and in section 3.4 we will explain that such a multivariable singularity may occur for simple, no-split HENs.

Monovariable singularity

The matrix in Eq. 3.4 may have no monovariable singularities. However, if the hot and the cold inlet temperatures are varied in opposite directions, the combined effect on the outputs may of course become zero. The conditions may be expressed as:

$$\Delta T_i^h = -\frac{P^h}{1-P^h}\Delta T_i^c \Rightarrow \Delta T_o^h = 0 \tag{3.9}$$

$$\Delta T_i^h = -\frac{1-P^c}{P^c}\Delta T_i^c \Rightarrow \Delta T_o^c = 0 \tag{3.10}$$

In section 3.4 it is shown that manipulating an inner match in HENs with match heat load loops may change both the hot and the cold inlet temperature of another match. The effects will have opposite signs so that the conditions for singularity in Eq. 3.9 or 3.10 may be fulfilled.

Propagation of temperature variations in HENs

Fact 1: A positive (negative) temperature change in a HEN has a positive or zero (negative or zero) effect on all other temperatures.

Proof: The hot and cold thermal effectiveness in the steady-state equation for single heat exchangers are physically bounded by zero and unity. The boundaries are independent of heat exchanger type and fluid properties, and from Eq. 3.4 it is then clear that a temperature disturbance cannot change sign (or even increase in size) when traversing a heat exchanger. In HENs there may be feedback loops, but this feedback will always be positive from the same reasons (see Fact 2).

Fact 2: Temperature disturbances are naturally dampened in HENs.

Proof: Let g_T^k denote the transfer function between an inlet temperature and an outlet temperature of exchanger k. From Eq, 3.6 we see that g_T^k will be given by the thermal effectiveness and be bounded between zero and unity.
Case I: The downstream path is not part of a loop. A loop exists if there is a natural feedback in the HEN, i.e., a stream temperature variation affect itself (a network with a loop is shown in Fig. 1.2). With no loops we have a simple series interconnection and the overall transfer function becomes:

$$g_T^{tot} = \prod_{k=1}^{N_{hx}} g_T^k \tag{3.11}$$

It then follows from $0 < g_T^k < 1$ that

$$0 < g_T^{tot} < 1 \tag{3.12}$$

Case II: The downstream path is part of a loop. Let g_{direct} denote the direct transfer function and g_{loop} the loop transfer function. Since the loop gain is positive, the "closed-loop" transfer function is given by:

$$g_T^{tot} = \frac{g_{direct}}{1 - g_{loop}} \tag{3.13}$$

where g_{direct} and g_{loop} are given by expressions similar to Eq. 3.11 and thus are bounded between zero and unity. Note that loops in HEN increase the gain since $1/(1-g_{loop}) > 1$, but still $g_T^{tot} < 1$ as shown next. Let k denote the match where we "enter" the loop, see Fig. 3.2. Then g_{direct} contains the term g_T^k and g_{loop} the term $1 - g_T^k$ (only true at steady-state), that is we may write:

$$g_T^{tot} = \frac{\hat{g}_{direct} g_T^k}{1 - \hat{g}_{loop}(1 - g_T^k)} \tag{3.14}$$

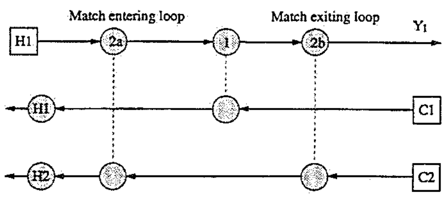


Figure 3.2: Illustration of loops and "entering" and "exiting" matches.

Substituting $h = 1 - g_T^k$ yields

$$g_T^{tot} = \hat{g}_{direct} \frac{1-h}{1-\hat{g}_{loop}h} \tag{3.15}$$

and since $0 < h < 1$ it is clear that $0 < g_T^{tot} < 1$.

This means that temperature disturbances that propagates in HENs may never change sign, and that they are naturally dampened.

With approximately equal heat capacity flowrates ($R^h \approx R^c \approx 1.0$), the effectiveness is often around 0.5 for typical process exchangers. This means that temperature disturbances that traverses several heat exchangers are naturally dampened, and that feedback control to reject such disturbances is not needed.

3.2.4 Steady-state effects of flowrate variations

The thermal effectiveness is a function of heat capacity flowrate ratio (e.g. Eq. 3.5), so flowrate changes have a nonlinear effect on the output temperatures. Furthermore, film coefficients (h) increases with flowrate, so flowrate variations also affect the thermal effectiveness through the overall heat transfer coefficient. In our model we use $h \sim w^m$ and $1/U = 1/h^h + 1/h^c$ where the exponential flowrate dependence $m = 0.8$as recommended by Jegede (1990). We assume in the following incompressible flow.

Single heat exchanger

Starting from Eq. 3.4 the linear gains may be expressed as (see appendix of Ch. 2 for a more complete derivation):

$$\begin{bmatrix} \Delta T_o^h \\ \Delta T_o^c \end{bmatrix} = G_w(0) \begin{bmatrix} \Delta w^h \\ \Delta w^c \end{bmatrix} = (T_i^h - T_i^c) \begin{bmatrix} -\frac{\partial P^h}{\partial w^h} & -\frac{\partial P^h}{\partial w^c} \\ \frac{\partial P^c}{\partial w^h} & \frac{\partial P^c}{\partial w^c} \end{bmatrix} \begin{bmatrix} \Delta w^h \\ \Delta w^c \end{bmatrix} \tag{3.16}$$

In words, the linear gain from flowrates to temperatures is the inlet temperature difference of the two streams times the change in thermal effectiveness.

For countercurrent heat exchangers (Eq. 3.5) the steady-state gains may be expressed analytically, even for flowrate dependent heat transfer coefficients.

$$\frac{\partial P^h}{\partial w^h} = \frac{1}{w^h} \frac{(R^h(a-1) + N_{TU}^h(b(1-R^h)))a}{(1-R^h a)^2}; \quad R^h \neq 1 \tag{3.17}$$

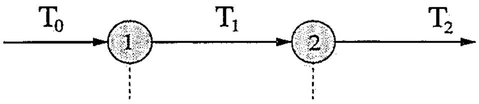


Figure 3.3: Flowrate disturbances affect all intermediate temperatures

$$\frac{\partial P^h}{\partial w^h} = \frac{1}{w^h} \frac{N^h_{TU}(N^h_{TU} + 2(1 - \frac{mh^c}{h^h+h^c}))}{2(N^h_{TU}+1)^2}; \quad R^h = 1 \tag{3.18}$$

where $a = \exp(-N^h_{TU}(1-R^h))$ and $b = (R^h \frac{mh^c}{h^h+h^c} - \frac{mh^c}{h^h+h^c} + 1)$

Propagation of flowrate variations in HENs

When flowrate disturbances propagate through heat exchangers in series, the effect on the outlet temperatures will be a combination of the direct effect of the flowrate change in the last exchanger and the indirect change of the inlet temperature to the last exchanger. For example, consider two exchangers in series as shown in Fig. 3.3. The effect of a flowrate change on the outlet temperature of the first exchanger is given by

$$dT_1 = \underbrace{\frac{\partial T_1}{\partial w}}_{g^1_w} dw \tag{3.19}$$

The change in the outlet temperature of the second exchanger may be expressed by the total differential

$$dT_2 = \underbrace{\frac{\partial T_2}{\partial w}}_{g^2_w} dw + \underbrace{\frac{\partial T_2}{\partial T_1}}_{g^2_T} dT_1 \tag{3.20}$$

and we find the expression for the overall effect

$$\frac{dT_2}{dw} = g^{tot}_w = g^2_w + g^2_T g^1_w \tag{3.21}$$

The generalization of Eq. 3.21 to N heat exchangers in series is straightforward:

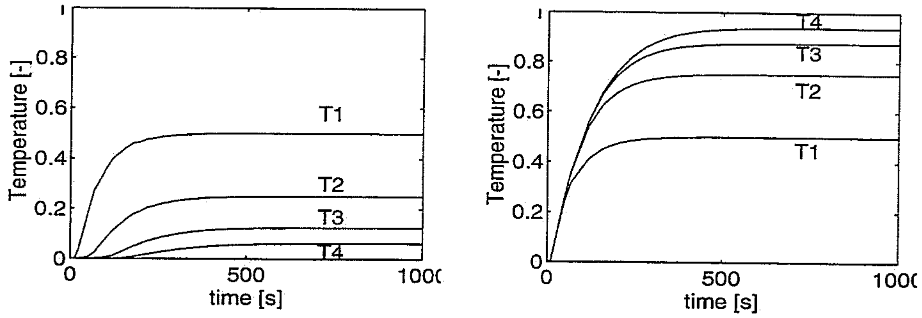
$$g^{tot}_w = g^N_w + g^N_T g^{N-1}_w + ... + g^2_T g^3_T ... g^N_T g^1_w \tag{3.22}$$

By defining $g^{N+1}_T = 1$ Eq. 3.22 may then be expressed as

$$g^{tot}_w = \sum_{i=1}^{N} g^i_w (\prod_{j=i+1}^{N+1} g^j_T) \tag{3.23}$$

Since the thermal effectiveness g^j_T is bounded between zero and unity, the maximum and minimum steady-state effects from flowrate variations may be expressed as:

$$g^N_w \leq g^{tot}_w \leq \sum_{i=1}^{N} g^i_w \tag{3.24}$$



a) Temperature disturbance

b) Flowrate disturbance

Figure 3.4: Step responses for 4 identical heat exchangers in series

In cases where all single heat exchanger transfer functions are identical Eq. 3.23 may be simplified using the result for geometric series:

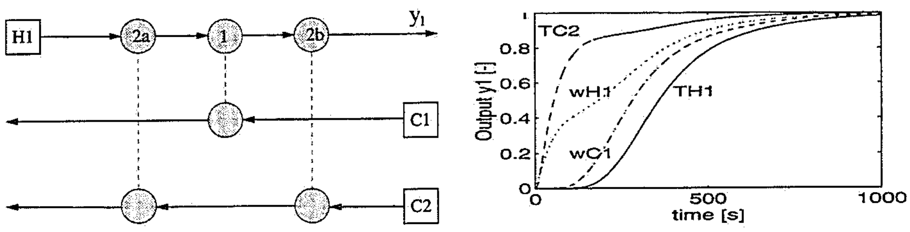
$$g_w^{tot} = g_w(1 + g_T + (g_T)^2 + ... + (g_T)^N) = g_w \frac{1-(g_T)^{N+1}}{1-g_T} \approx \frac{g_w}{1-g_T} \quad N \geq 2 \quad (3.25)$$

since $g_T < 1$. Note that the approximation is not limited to steady-state.

This shows that flowrate disturbances are fundamentally different from temperature disturbances and that they may be difficult to reject. This is illustrated in Fig. 3.4 where the temperature and flowrate disturbance propagation over identical heat exchangers in series are compared. The disturbances have been scaled so that the steady-state effect over the first exchanger is 0.5 for both disturbances. The effect of the temperature disturbance decreases towards zero whereas the effect of the flowrate disturbance increases towards unity with increasing number of heat exchangers in series.

Fact 3: A hot (cold) stream flowrate increase has a positive or zero (negative or zero) effect on all temperatures.

Proof: Case 0: A single heat exchanger. In this case Fact 3 holds since $(\partial P^h/\partial w^h)$ and $(\partial P^c/\partial w^c)$ are negative and $(\partial P^h/\partial w^c)$ and $(\partial P^c/\partial w^h)$ are positive, respectively. Note that the heat load on a heat exchanger increases with both hot and cold flowrate. Case I: A single match on the disturbed stream. In this case the disturbance will propagate as a pure temperature disturbance from the cold side throughout the HEN. Case II: Several matches on the disturbed stream. All outlet temperatures of the matches on the disturbed stream will increase from the primary flowrate effect. The downstream matches on the disturbed stream will get a secondary temperature effect, but the secondary effect will strengthen the primary effect. Further downstream the disturbance propagates as a temperature disturbance.



a) Network b) Step responses (same steady-state gains)

Figure 3.5: Effect of step disturbances (on output y_1)

3.2.5 Dynamic considerations

Stability

Heat exchangers simply transfer heat from the hot stream to the cold stream; there is no energy generation term. Thus, single heat exchangers are open-loop stable.

Fact 4: All HENs are open-loop stable.

Proof: Case I: HENs without loops and without parallel downstream paths. Since single heat exchangers are stable, HENs without loops must be stable from Eq. 3.11.
Case II: HENs without loops and with parallel downstream paths. Parallel downstream path may never cause a instability because the two effects have opposite signs.
Case III: HENs with loops. Since single heat exchangers are stable, HENs with loops are stable from Fact 2.

Temperature disturbances

Heat exchangers often have some sort of countercurrent "plug" flow in order to get good thermal effectiveness. The response from inlet to outlet temperature on the same side is of high-order and slow due to large mass and energy holdups, whereas the response to the outlet temperature on the opposite side is faster due to the more direct effect.

The dynamics of different temperature disturbances may vary considerably, and this is illustrated in Fig. 3.5 where the disturbances have been scaled so that the steady-state effects are unity. The effect of a temperature change of stream $H1$ will be slow due to mass and energy holdup in the three matches and mass holdup in the connecting pipes, whereas the effect of temperature change of stream $C2$ is fast because the first match on this stream is the final match on the controlled stream and because this match as usual has countercurrent flow.

Flowrate disturbances

With incompressible fluids flowrate changes have immediate effect on the downstream flow. Flowrate disturbances initially affect the heat transfer by changing the heat transfer coefficient. With several heat exchangers in series flowrate disturbances the

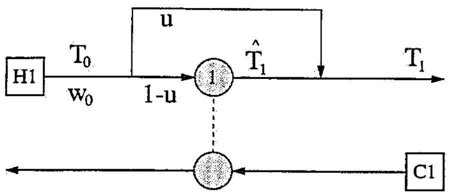


Figure 3.6: Derivation of effect of bypass manipulation.

effect on the final temperature is very fast, whereas the approach towards to steady-state of may be slow because the full effect also include changes in temperatures. This can be illustrated with the HEN in Fig. 3.5a where a flowrate disturbance of stream $H1$ may be fast and difficult to reject. In Fig. 3.5b the effect of flowrate changes in streams $H1$ and $C1$ are compared. The response from flowrate variations in stream $C1$ will be considerably delayed because the flowrate disturbance propagate as a temperature disturbance from the hot outlet of match 1.

3.2.6 Effects of bypass manipulations

The gains for bypass manipulations may be derived from the gains for flowrate disturbances.

Single heat exchanger

We are seeking to find the effect of a change in bypass fraction (u) on the downstream temperature (T_1), see Fig. 3.6. An energy balance over a mixer downstream the bypassed match yields:

$$T_1 = (1-u)\hat{T}_1 + uT_0 \tag{3.26}$$

abd we have the differential:

$$dT_1 = (T_0 - \hat{T}_1)du + (1-u)d\hat{T}_1 \tag{3.27}$$

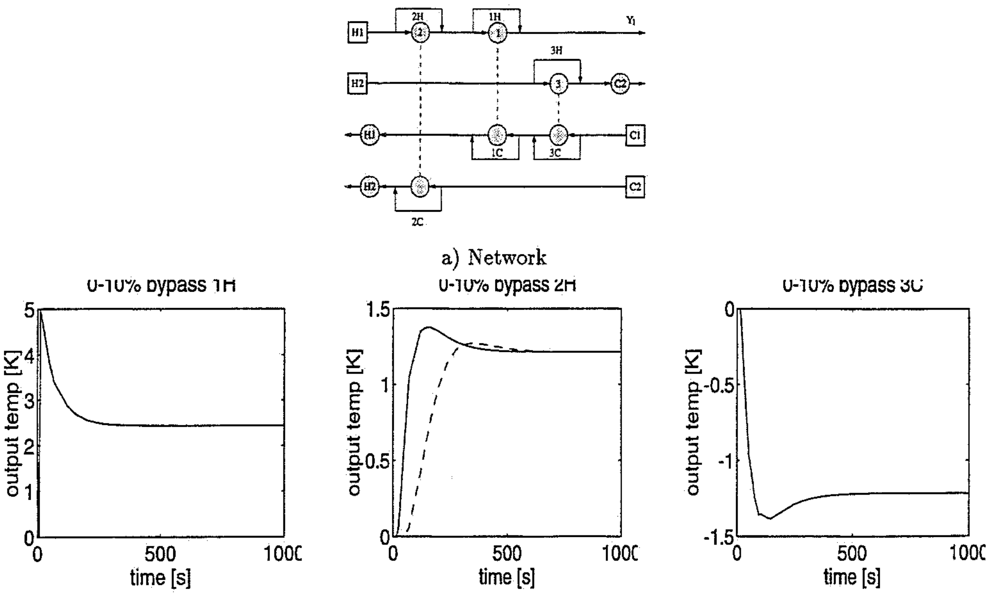
Thus, the overall effect is:

$$g = \frac{dT_1}{du} = (T_0 - \hat{T}_1) + (1-u)\frac{\partial \hat{T}_1}{\partial u} = (T_0 - \hat{T}_1) - wg_w \tag{3.28}$$

where $w = w_0(1-u)$ is the heat capacity flowrate through the exchanger and $g_w = \partial\hat{T}/\partial w$ is the gain for a flowrate change as given by Eq. 3.16. The overall effect consists of two opposing effects:

1. changing the flow ratio of the inlet streams to the mixer (a fast effect).

2. changing the temperature of the stream from the heat exchanger to the mixer (a slower effect).



a) Network

b) Response from bypass 1H

c) Response from bypass 2H (Dashed line: With pipe holdup included

d) Response from bypass 3C

Figure 3.7: Typical responses for y_1 from bypasses around final and upstream matches

Thus, bypass manipulations have an immediate effect on the outlet temperature on the bypassed side. This direct effect is partly counteracted by the slower effect of the increased temperature change over the exchanger. Because the initial effect always dominate, bypassing a heat exchanger always gives overshoot-type responses (never inverse responses) corresponding to a zero in the left-half-plane. Typical responses are shown in Fig. 3.7. Downstream the bypassed match, bypass manipulations propagate as temperature disturbances, i.e., the effect is both slowed down and reduced.

Fact 5: Bypass manipulations propagate as a temperature increase from the hot side and a temperature decrease from the cold side of the bypassed match.

Proof: From an overall energy balance over the bypassed match (see Fig. 3.6), increasing the bypass fraction decreases the flow through the exchanger, which decreases the heat transferred. Thus, bypassing a match increases the hot outlet temperature and decreases the cold outlet temperature. Fact 5 then follows since there is no flowrate variation in the rest of HEN.

From Fact 5 bypassing a match in HENs introduces two temperature disturbances, one positive and one negative. If the bypassed match is an inner match with downstream matches on both sides, both disturbances may propagate through the network, and the overall effect may be either positive or negative.

Fact 6: Bypass manipulations of matches may depending on problem parameters either increase or decrease a temperature (output) if and only if there are parallel (independent) downstream paths from the two sides of the manipulated match to the temperature.

Proof: Case I: One downstream path from the bypassed match to output. The effect of the bypass manipulation will then propagate as one temperature disturbance, and the direction of the effect is independent of problem parameters from Fact 1.
Case II: Dependent downstream paths. Two downstream paths exist there is both a primary effect from the hot (cold) side and a secondary effect from the cold (hot) side of the manipulated match to the output. The downstream paths are dependent if the secondary effect from the cold (hot) side affect the output through the hot (cold) side of the manipulated match. The two effects are opposing from Fact 5, but analogously to the proof of Fact 2 it may be shown that the primary effect always dominates.
Case III: Parallel (independent) downstream paths. Parallel and independent downstream paths exist if neither of the downstream paths traverses the manipulated match, and may only occur if an inner match is manipulated. From Fact 5 the effects are opposing, and both effects may be expressed through individual heat exchanger effects, i.e., by Eq. 3.11. With downstream paths to the same temperature either one may dominate depending on problem parameters.

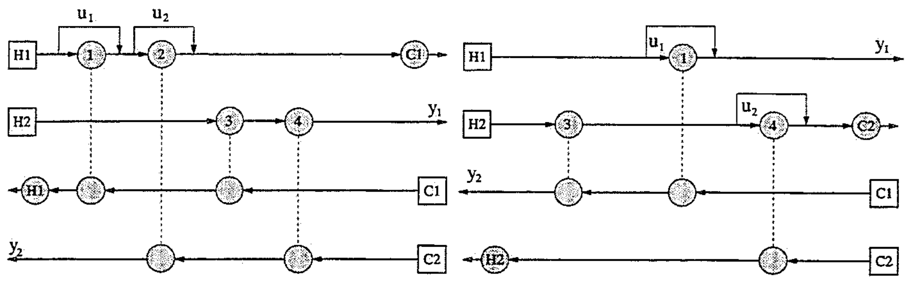
3.3 Structural singularities

Singularities arise when an input or a combination of inputs have no effect on the output(s), and identification of possible singularities is very important for controllability assessment. Singularites that depend on plant structure only are structural, whereas parameter singularities occur if the plant is singular for some specific parameter combinations only. Structural singularities for HENs are discussed by Georgiou and Floudas (1990), who suggested to design HENs that are structurally singular from the disturbances. This may be good idea for plants with one or a few dominating disturbances, but is impossible in the general case where all inlet temperatures and flowrates should be regarded as disturbances. Work on parametric singularities in HENs, and their impact on control, seems to be missing in the literature.

Mathematically, a plant $G(s)$ is functional controllable if the rank of $G(s)$ is equal to the number of outputs, and is not if $G(s)$ somehow is singular (Rosenbrock, 1970). Since the requirement is fundamental and often easy to check, it can be recommended as the first test of a proposed control structure. In the following we describe four cases of structural singularities in HENs.

3.3.1 No downstream paths from inputs

An obvious way to get a structural singular system is when none of the inputs affect one of the outputs, i.e., a row in the plant transfer function only has zero elements. For HENs this occurs if there is no downstream path from any of the inputs (i.e. matches if bypasses are used) to one of the outputs. In Fig. 3.8a none of the inputs affect output y_1, which yields a structural singular system. The plant transfer function for



a) None of the inputs affect output y_1 b) Input u_2 affects none of the outputs

Figure 3.8: Structural singularities in HENs

this system is given by

$$G(s) = \begin{bmatrix} 0 & 0 \\ g_{21}(s) & g_{22}(s) \end{bmatrix}$$

3.3.2 No downstream paths to outputs

The other obvious way to get a singular system is when a column in the plant transfer function only has zero elements. For HENs this occurs if there is no downstream path from the manipulated match to any of the outputs. In Fig. 3.8b input u_2 affects none of the outputs, which yields a structural singular system. The plant transfer function for this system is given by

$$G(s) = \begin{bmatrix} g_{11}(s) & 0 \\ g_{21}(s) & 0 \end{bmatrix}$$

For the example in Fig. 3.8b, the outlet temperatures of stream $H2$ and $C2$ would be controlled by manipulating the final utility exchanger (utility-controlled output). These control loops are as usual *not* included in the figure. From the structure, we see that input u_2 only affects the utility-controlled outputs, and bypassing match 4 gives a double energy penalty. From this simple observation a rule for bypass placement may be derived: *Never bypass matches that only affect utility-controlled outputs.* For this example, one must bypass both match 1 and match 3 to get a structurally controllable plant.

3.3.3 Downstream paths coincide

Structural singularity arises if both manipulated variables affect the outputs through the same downstream path, see Fig. 3.9a. In this case, the plant transfer function may be expressed through the intermediate cold inlet temperature of match 3 ($y_0 = u_0$) as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} g_{10} \\ g_{20} \end{bmatrix} y_0; \quad y_0 = \begin{bmatrix} g_{01} & g_{02} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{3.29}$$

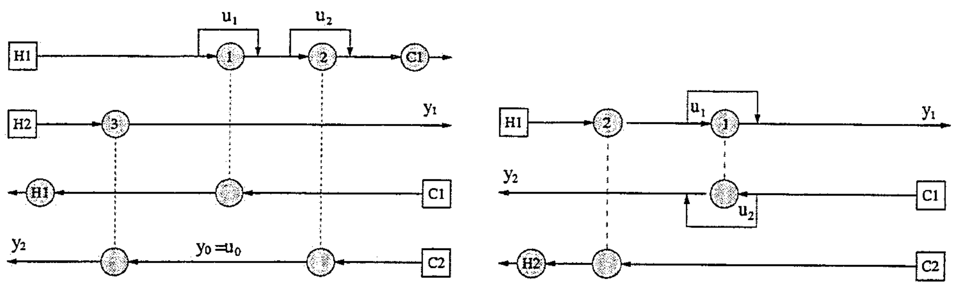


Figure 3.9: Structural singularities in HENs

and we have

$$G(s) = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} = \begin{bmatrix} g_{10}(s) \\ g_{20}(s) \end{bmatrix} \begin{bmatrix} g_{01}(s) & g_{02}(s) \end{bmatrix} = \begin{bmatrix} g_{10}(s)g_{01}(s) & g_{10}(s)g_{02}(s) \\ g_{20}(s))g_{01}(s) & g_{20}(s)g_{02}(s) \end{bmatrix} \tag{3.30}$$

and G is singular both at steady-state and dynamically.

3.3.4 Bypasses on both hot and cold side

If one places single bypasses on both sides of a heat exchanger, see Fig. 3.9b, $G(s)$ becomes singular at steady-state since the heat heat load is the same on both sides at steady-state (i.e. there is only one degree of freedom per exchanger at steady-state). The plant transfer function at steady-state for this system may be expressed as

$$G(0) = \begin{bmatrix} g_{11}(0) & g_{12}(0) \\ g_{11}(0)R_1^h & g_{12}(0)R_1^h \end{bmatrix}$$

where R_1^h is the (hot side) heat capacity flowrate ratio of match 1. G is linearly dependent for all problem parameters. Dynamically, the system is not singular, but only rarely will one be able to take advantage of this.

3.4 Parametric singularities and right-half-plane zeros

A right half plan (RHP) transmission zero of the plant transfer function limits the achievable bandwidth regardless of the controller used (Rosenbrock, 1970). When decentralized control is used, one should also avoid RHP zeros in the elements in order to maintain stability of the individual loops.

Observation for HENs: Plants that may become parametrically singular at steady-state for a certain set of parameters may have a RHP-zero.

This means that there is an important connection between steady-state and dynamics of HENs, and that network and control structures that may give RHP zeros are easy to identify. For HENs we divide the cases of parametric singularity into five categories; 1) Downstream mixers (i.e., downstream a heat exchanger), 2) Upstream mixers, 3) Splits, 4) Inner matches and 5) Combining matches. The first four categories are monovariable zeros, whereas the final category is a multivariable zero. In the following we identify and describe the competing effects and show how the response may or may not be inverse depending on problem parameters. Fig. 3.10 summarizes the main results, but we will present numerical examples and show how they may occur in HENs in the following sections. Note that these control problems may occur in designs derived with modern synthesis techniques.

3.4.1 Downstream mixers

In section 3.2.6 we explained that remixing a bypass flow with the main stream through the exchanger (Fig. 3.10a) give competing effects, but that the faster flow effect always dominate yielding overshoot-type responses (Fig. 3.10b). This means that only left-half-plane (LHP) zeros may occur.

In other cases mixing may yield a right-half-plane (RHP) zero or parametric singularity. Mixing a stream downstream a heat exchanger with an independent stream as in Fig. 3.10c may yield an inverse response. When mixing two hot (cold) streams, such mixers may give an inverse response if the manipulated stream through the exchanger is the colder (hotter) stream. A numerical example is shown in Fig. 3.10d. The negative effect of increasing the flowrate of the colder of the two streams to the mixer may be counteracted by the slower, positive effect of increasing the temperature of this stream. The two effects are the same as when remixing a bypass flow, but in this case the slower effect may dominate because they are independent.

A stream split with downstream mixing may yield two RHP-zeros. This is discussed in section 3.4.3.

3.4.2 Upstream mixers

Mixers upstream heat exchangers may also yield an inverse response, see Fig. 3.10e. When mixing two hot (cold) streams, such upstream mixers may give inverse response if the manipulated stream is the colder (hotter) stream. Increasing the manipulated stream increases the flowrate to the heat exchanger, a positive effect, but decreases the inlet temperature to the heat exchanger, a negative effect. Either one may dominate depending on problem parameters. Note that there are opposing effects to both outlet temperatures, but that the problem parameters that give parametric singularity are different. Furthermore, two RHP-zeros are possible to the opposite side, see the numerical example in Fig. 3.10f. At high frequency the flowrate effect dominates, but the temperature effect may dominate at intermediate frequency due to the countercurrent flow in the heat exchanger even when the flowrate effect dominates at steady-state.

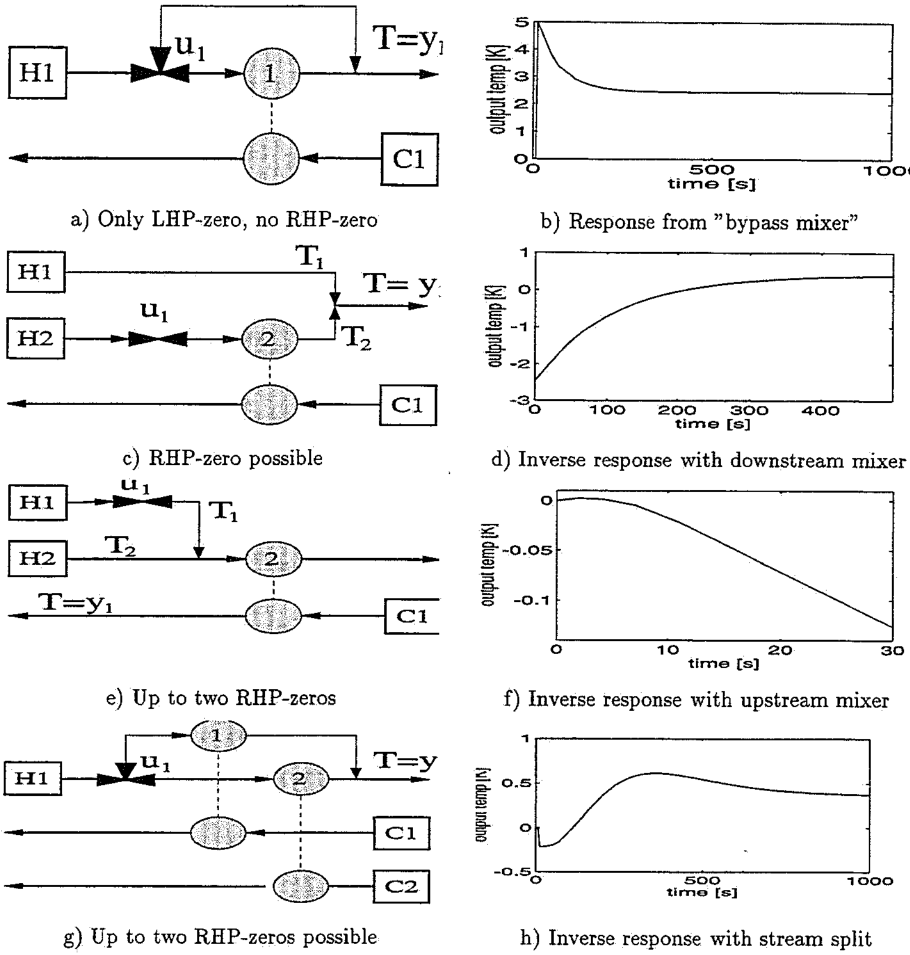


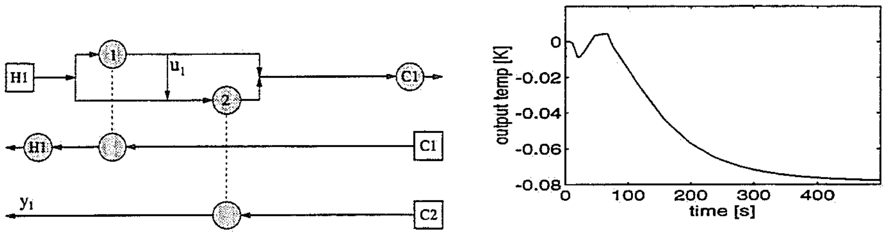
Figure 3.10: Mixers may yield zero, one or two RHP-zeros

3.4.3 Splits (parallel mass flows)

Split fractions may be used as manipulated inputs instead of bypass fractions. For example, in Fig. 3.10g a hot stream is split.

Manipulating split fractions gives competing effects; the heat loads on the exchangers on one of the branches increase whereas the heat loads on the exchangers on the other branch decrease. This may give an inverse response, see Fig. 3.10h. The sum of the heat load changes may be positive or negative depending on operating point, and at some intermediate split fraction the steady-state gain will be zero. Such parallel heat exchange may be considered as a special case of downstream mixing, but with a simultaneous change in both the mixed flows. With different residence times, the sign

Figure 3.11: Possible RHP-zero and inverse response with stream mixing



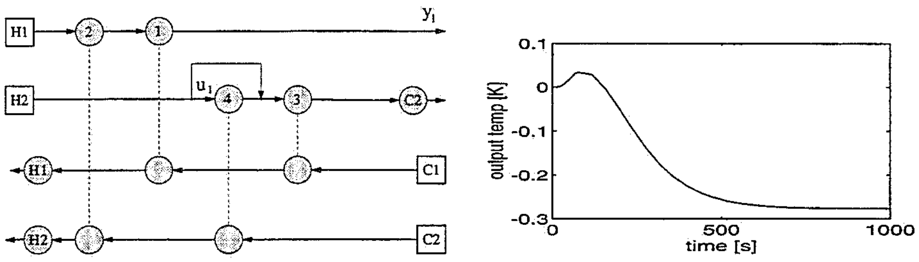
a) Network b) Inverse response

Figure 3.12: Possible RHP-zero and inverse response with a combination of serial and parallel heat exchange.

of the gain may change twice. Initially, the temperature of the remixed stream may increase or decrease depending on the operating point. At some intermediate time, the faster of the two branches will dominate, and the sign may have changed. Finally, the slower of the two branches may have reversed the sign again at steady-state. The presence of the inverse response requires very long time constants in the corresponding control loops, and such split fractions should only be used for supervisory control (energy optimization), not for regulatory control (rejection of dynamic disturbances). Note that the split fraction may safely be used to control one of the streams that are not split (in this case one of the cold streams) as this gives no competing effects.

3.4.4 Combination of series and parallel heat exchange

Designs with a combination of series and parallel heat exchange have been suggested both to conventional HEN problems and flexibility problems. An example is shown in Fig. 3.12a. The main motivation for such designs is to reduce the number of units. However, the possibility for RHP-zeros make these designs less desirable. Manipulating the flow that combines the two branches (u_1 in Fig. 3.12a) gives competing effects due to an upstream mixer. Increasing this flow, increases the flow through match 2 which increases the heat load. However, increasing u_1 will also decrease the inlet temperature to match 2, which decreases the heat load. Either the positive flowrate effect or the negative temperature effect may dominate, and an inverse response is possible, see Fig. 3.12b.



a) Network b) Inverse response

Figure 3.13: Parallel downstream paths from inner match

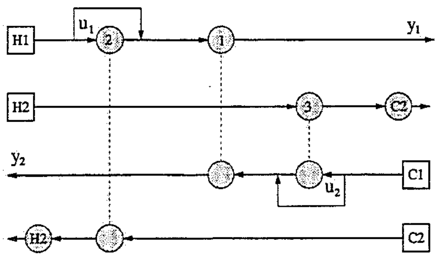


Figure 3.14: Combining match with possible multivariable RHP-zero.

3.4.5 Inner match (parallel energy flows)

Inner matches are matches with downstream matches on both sides. If an inner match is bypassed, and the inner match is part of a loop, there may be two parallel downstream paths to a stream temperature. As explained in section 3.2.6 the effects will be opposing, and parametric singularity and a RHP-zero may occur. In Fig. 3.13a, input u_1 (hot bypass on match 4) affects output y_1 (outlet temperature of hot stream 1) through matches 3 and 1 (positive gain) and through matches 2 and 1 (negative gain). These downstream paths are independent as neither traverse the manipulated match (match 4). A typical step response is shown in Fig. 3.13b. For this example all heat capacity flowrates are equal.

3.4.6 Multivariable RHP-zero: Combining match

In section 3.2.3 we explained that using the inlet temperatures to control the outlet temperatures of a heat exchanger may yield a multivariable singularity and RHP-zero. Here we would like to point out that this may occur even for simple HENs where bypasses are used as manipulated inputs. If two upstream matches are used to control the two outputs on a double output match as in Fig. 3.14 this may occur. Since all four transfer functions in a 2×2 system or subsystem traverses match 1 from an inlet to an outlet temperature and combines the input/output transfer functions, we denote it a *combining match.* All input combinations that gives a combining match may have a multivariable singularity, the criterion for singularity also holds true if there are additional matches between the combining match and one of the outputs or between one of the inputs and the combining match. An important rule for bypass placement may be derived: Never use a pair of bypasses that affect the outputs through a combining match.

3.5 Time delays

Time delays in control loops of HENs are due to

1. Mass holdup (fluid capacitance) and energy holdup (wall capacitance) in heat exchangers
2. Mass holdup (fluid capacitance) in connecting pipes and bypasses
3. Actuator and measurement dynamics

We will explain how the time delay vary with plant structure through the example in Fig. 3.7a. For all the examples we approximate actuator and measurement dynamics with a delay of 10 seconds.

3.5.1 Direct effect bypasses

For incompressible fluids, the initial effect from increasing the bypass fraction is immediate except for possible response delay from actuator and measurement. A typical response is shown in Fig. 3.7b.

3.5.2 Bypass on upstream match on the controlled stream

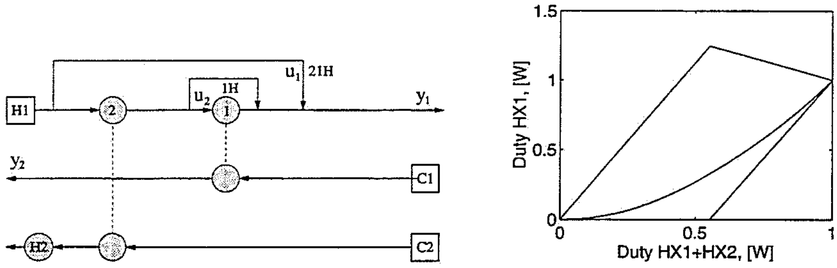
When heat exchanger dynamics are approximated with a lumped model, a high model order is recommended (e.g., Mathisen *et al.*, 1993)* . In order to get the effect of an apparent time delay for temperature changes. A typical example would be to bypass match 2 to control output y_1 in Fig. 3.7a. The step response is shown in Fig. 3.7c.

When upstream matches are bypassed and used as manipulators, the pipe holdup between the matches affect the delay in the response. For comparison, a time response with a pipe holdup between matches 2 and 1 equal to the match holdup is included in Fig. 3.7c (dashed line).

3.5.3 Bypass on upstream match on opposite side

Most heat exchangers are countercurrent, and this may make it desirable to use upstream matches on the opposite side of the controlled stream, e.g., match 3 in Fig. 3.7a. The step response from a cold bypass around match 3 is shown in Fig. 3.7d. A comparison between Fig. 3.7c and d indicate that the apparent delay from bypass 3C is smaller than from bypass 2H as expected because the heat exchangers are countercurrent. Note that additional pipe holdup between matches 3 and 1 may alter this preference order.

*corresponds to chapter two of this thesis



a) Network

b) Operating range with two single bypasses (limited by straight lines) and single and multi-bypass (below curved line)

Figure 3.15: Operating range for alternative bypass for network with double output match

3.6 Input constraints

Input constraint problems largely depend on problem parameters, e.g., on the size of disturbances (larger inlet temperature and flowrate variations). However, in section 3.4 we discussed cases where mainly the heat exchanger network and control configuration gave input constraint problems due to competing effects. From the discussion in sections 3.2 and 3.5 it is also clear that long downstream paths (several heat exchangers) between manipulated inputs and controlled outputs will give problems with input constraints. Here we will discuss how multi-bypasses may yield input constraint problems for some special multivariable problems.

3.6.1 Operating range with multi-bypass

For some types of HENs it may be desirable to use a multi-bypass. One important example is HENs that include a *double output match.* Double output matches are matches where both outlet temperatures are controlled outputs, and it may be recommended to install a multi-bypass as shown in Fig. 3.15a to get a fast response to both outputs.

The operating range may seem unchanged after installing the multi-bypass since the match duties are the same both with zero and unity bypass fractions. However, this a multivariable problem, and the operating range is in fact much smaller with the bypasses in Fig. 3.15a compared two single bypasses, see Fig. 3.15b. Note the following: 1) The control range with single bypasses are limited by straight lines. Heat exchangers are linear in temperature, and the effect of bypass manipulations propagates linearly downstream the remixer. 2) Closing single bypass 2H has a positive effect on the heat heat load on match 1. The hot outlet temperature of match 1 is the inlet temperature to match 1, and increasing this temperature increases the temperature driving forces of match 1 increases. 3) Closing the multi-bypass decreases both match duties. The effect on match 2 is equal to the single bypass 2H. The effect on match 1 will be the combined effect of a flowrate decrease and a temperature decrease. Since both effects are negative, the overall effect is a large decrease in the heat load on match 1 and this gives a line that curves downwards on the plot.

The control range when using a multi-bypass may be reduced to 20% – 40% of the control range with two single bypasses, and this may give severe problems with input constraints.

3.7 Interactions

In this section we consider the effect of interactions as given by the elements of the plant transfer function G. A decentralized control system with simple PI or PID controllers is desirable. Interactions between the control loops may seriously affect the control performance, or even make independently tuned control loops unstable. The interactions may be one-way or two-way, and two-way interactions will usually be worst. In the following we will explain the structural differences between networks with one- and two-way interactions, and networks without interactions.

3.7.1 Plants without interaction

HENs without loop interaction are plants where only final utility exchangers are manipulated inputs. Only for such plants, the plant transfer function becomes diagonal: $G = diag(g_{ii})$. Manipulating the heat load on a process exchanger will always affect at least one hot and one cold network outlet temperature, and we assume that all network outlet temperatures are controlled outputs.

3.7.2 Plants with one-way interaction

A HEN include a loop if there is a downstream path from one of matches via at least one other match and back to the match one started from (i.e. natural feedback loops). Matches part of loops yield two-way interactions, so to get plants with only one-way interaction such matches must not be manipulated. Many HENs with minimum number of *process exchangers* yield plants with only one-way interaction. An example is shown in Fig. 3.16. The plant transfer function is in this case tridiagonal:

$$G = \begin{bmatrix} g_{11} & g_{12} \\ 0 & g_{22} \end{bmatrix} \tag{3.31}$$

Pairing of the control loops is of course straightforward as RGA becomes equal to the identity matrix (when numbering the inputs as in the figure).

3.7.3 Plants with two-way interaction

Network with loops

For HENs with heat load loops consisting of only process heat exchangers, there may exist an inner match with two parallel downstream paths to a controlled output, see

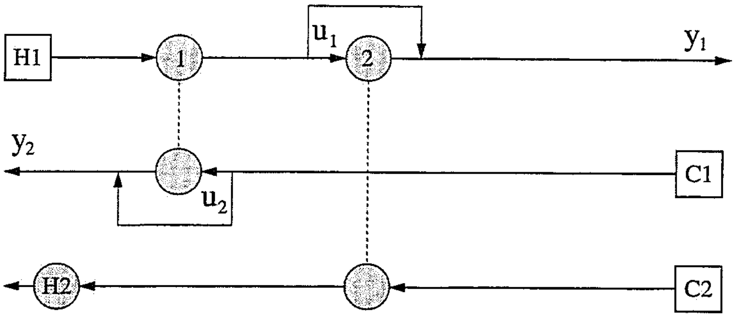


Figure 3.16: HEN with minimum number of matches and only one-way interaction

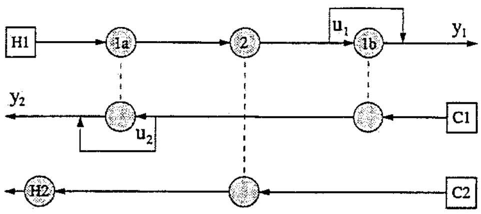


Figure 3.17: Network with loop and two-way interaction.

section 3.4.5. But even without such manipulators, HENs with process heat load loops give systems with interaction. A simple example where the heat load loop consists of two matches between the same two streams is shown in Fig. 3.17.

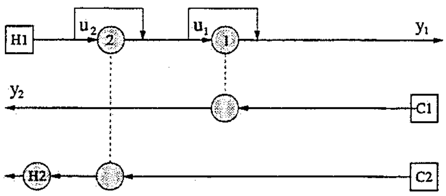
Double output matches

When both outputs of one match are controlled outputs, using single direct effect bypasses yield a singular system, see section 3.3.4. Using upstream matches on both sides yields a combining match with a possible multivariable RHP zero, see section 3.4.6. Therefore, one needs one bypass around the double output match, and one bypass around an upstream match. The resulting system is a 2×2 control problem with two-way interaction between the control loops. Since the structure of the problem is symmetric assume that there is an upstream match on the hot side only, see Fig. 3.18a. In Fig. 3.18a hot, single bypasses are used. The steady-state gains may be expressed as

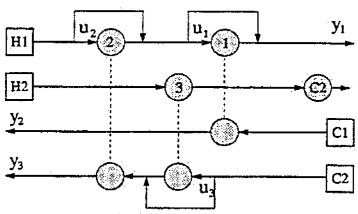
$$G(0) = \begin{bmatrix} g_{11}(0) & g_{12}(0) \\ -R_1^h g_{11}(0) & \frac{R_1^h P_1^h}{1-P_1^h} g_{12}(0) \end{bmatrix} \tag{3.32}$$

The ratio $g_{21}(0)/g_{11}(0)$ is equal to $-R_1^h$ because input u_1 manipulates the heat load of the match with the two outputs. The ratio $g_{22}(0)/g_{12}(0)$ is equal to $P^c/(1-P^h)$ from Eq. 3.6 because input u_2 affect both outputs through the hot inlet temperature to the double output match.

With the plant transfer function on this form, it is straightforward to compute the



a) 2 × 2 control problem.



b) 3 × 3 control problem.

Figure 3.18: Double output match yields multivariable control problems.

relative gain matrix (RGA):

$$\Lambda(0) = \begin{bmatrix} P_1^h & 1 - P_1^h \\ 1 - P_1^h & P_1^h \end{bmatrix} \tag{3.33}$$

The fact that $\lambda_{11}(0) = P_1^h$ shows that the preferred pairings are independent of temperatures and thus independent of the upstream match. Because thermal effectiveness P is bounded by $0 < P < 1$, so is $\lambda_{ij}(0)$. The thermal effectiveness often is about 0.5 and varies with operating point, so simple decentralized controllers may behave poorly. As large RGA-elements cannot occur, the plant will not be particularly sensitive to model uncertainty, and decoupling controllers may be applied (Skogestad and Morari, 1987). As an alternative one may use a multi-bypass around matches 2 and 1. This makes it possible to get direct effect bypasses in both control loops which is desirable. However, due to the restrictions on the operating range discussed in section 3.6.1, the multi-bypass should be installed in addition too, not instead of the single bypass on the upstream match. Also note that the use of multi-bypasses so that two inputs manipulate the same heat load yields RGA elements that exceeds unity at steady-state.

Double output match and output on upstream match (3×3)

An interesting special case of HENs with double output matches occurs if an outlet on the upstream match also is a controlled output. An example is given in Fig. 3.18b.

The steady-state gain matrix may be expressed as:

$$G(0) = \begin{bmatrix} g_{11}(0) & g_{12}(0) & g_{13}(0) \\ -R_1^h g_{11}(0) & \frac{R_1^h P_1^h}{1-P_1^h} g_{12}(0) & \frac{R_1^h P_1^h}{1-P_1^h} g_{13}(0) \\ 0 & -\frac{R_2^h}{1-P_1^h} g_{12}(0) & \frac{1-P_2^h}{P_2^h(1-P_1^h)} g_{13}(0) \end{bmatrix} \tag{3.34}$$

where the ratios $g_{32}(0)/g_{12}(0)$, $g_{23}(0)/g_{13}(0)$ and $g_{33}(0)/g_{13}(0)$ are derived from Eq. 3.6 similarly as for the 2×2 system.

Eq. 3.34 yields the following RGA at steady-state:

$$\Lambda(0) = \begin{bmatrix} P_1^h & (1 - P_1^h)(1 - P_2^c) & (1 - P_1^h)P_2^c \\ 1 - P_1^h & P_1^h(1 - P_2^c) & P_1^h P_2^c \\ 0 & P_2^c & 1 - P_2^c \end{bmatrix} \tag{3.35}$$

Note that the RGA only depends on the thermal effectiveness of the two matches with controlled outputs, and that all RGA elements are between zero and unity.

3.8 Conclusions

Important dynamic charactericstics may be described through the following facts:

1. A positive (negative) temperature change in a HEN has a positive or zero (negative or zero) effect on all other temperatures.

2. Temperature disturbances are naturally dampened in HENs.

3. A hot (cold) stream flowrate increase has a positive or zero (negative or zero) effect on all temperatures.

4. Bypass manipulations propagate as a temperature increase from the hot side and a temperature decrease from the cold side of the bypassed match.

5. Bypass manipulations of matches may increase or decrease a temperature (output) depending on problem parameters if and only if there are parallel (independent) downstream paths from the two sides of the manipulated match to the temperature.

6. All heat exchanger networks are open-loop stable.

Understanding about the dynamic behaviour is used to identify control limitations and explain how they may occur in HENs. Of particular importance is inverse responses due to RHP zeros. Possible RHP zeros in HENs may be divided into five categories:

1. Downstream mixers. Mixing two independent streams downstream a heat exchanger may give competing flowrate and temperature effects, and there may be one monovariable RHP zero.

2. Upstream mixers. Mixing to independent streams upstream a heat exchanger may also give competing flowrate and temperature effects, and there may be two monovariable RHP zeros.

3. Splits. Stream splits give parallel mass flows, and remixing the streams give parallel downstream paths that may give two monovariable RHP zeros.

4. Inner matches. Manipulating inner matches may give parallel energy flows, and a heat load loop consisting of only process exchangers may give independent, parallel downstream paths that may give a monovariable RHP zero.

5. Combining matches. For multivariable 2×2 problems, a multivariable RHP zero may occur if all four input-output effects traverse the same match.

The results on control limitations may be used to divide plants (HEN with control configuration) into different categories according to their expected control characteristics. The classification is based on network and control structure only, so any conclusions must be used with caution.

1. Plants with no interaction
2. Plants with single, direct effect bypasses and one-way interaction only
3. Plants with direct effect bypasses
4. Plants with fast, but not direct effect bypasses.
5. Plants with appreciable apparent time delay.
6. Plants with right half plane zeros.
7. Plants that are structural singular at steady-state
8. Plants that are structural singular (also dynamically)

Plants with no interaction are obtained by manipulating final heaters and coolers on all streams. This usually gives excess units and high capital cost. Furthermore, a certain heat load must be maintained for all the utility exchangers for all operating points. This will give excess utility requirements and high energy cost. Still, these plants are preferred from a control point of view. Thus, there is definitely a trade-off between controllability, energy and capital in HENs.

One way to resolve the trade-off could be to allow one-way interactions only. Plants with one-way interaction will usually have close to minimum number of units with many final utility exchangers.

However, two-way interactions between control loops manipulating matches are often a minor control problem. Good performance may be obtained with simple inverse-based controllers. Thus, plants of category three and four may sometimes be overall optimal, too.

Plants with considerable time delay or important RHP-zeros should be avoided.

Nomenclature

For the dynamic model

A - Heat exchanger area, $[m^2]$
a - Parameter in Eq. 3.17
b - Parameter in Eq. 3.17
h - Heat transfer coefficient, $[W/m^2K]$
N - Number, $[-]$
P - Thermal effectiveness, $[-]$
R - Heat capacity rate ratio, $[-]$
T - Temperature, $[K]$
t - Time, $[s]$
U - Overall heat transfer coeff., $[W/m^2K]$

w - Heat capacity flowrate, $[kW/K]$

greek
ΔT - Temperature difference, $[K]$
τ - Time constant, $[s]$

For control
$G(s)$ - Process transfer function matrix
$G_T(s)$ - Temperature disturbance transfer function matrix
$G_w(s)$ - (Heat capacity) flowrate disturbance transfer function matrix
$G_d(s)$ - Augmented disturbance transfer function matrix ($[G_T\, G_w]$)
$g_{ij}(s)$ - ij'th element of $G(s)$
$\hat{g}(s)$ - part of g
$g_{dik}(s)$ - ik'th element of $G_d(s)$
$u(s)$ - Vector of manipulated inputs
$y(s)$ - Vector of outputs

greek
$\Lambda(s)$ - Relative gain matrix
$\lambda_{ij}(s)$ - ij'th element of $\Lambda(s)$

superscripts
c - cold side/fluid
h - hot side/fluid
k - exchanger k
tot - total

subscripts
$direct$ - direct
hx - exchanger
i - inlet or index for outputs
j - index for manipulted inputs
k - index for disturbances or stream segments
$loop$ - loop
o - outlet
TU - transfer units

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