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Evaluation of HEN controllability

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***Abstract** In the last three decades the importance of resolve a robust, rigorous and operable heat exchanger networks (HEN) is boosted due to the change in the concepts of effective cost of a HEN several methodologies are applied to solve the operability aspects of a HEN including flexibility and controllability of a HEN in this work a systematic approach is introduced to solve the controllability issue for HENs.*

The work framework consist of two major steps where in the first step a disturbance propagation model for a HEN is constructed adopting Yang et.al disturbance model[1][2][3].

The second step is to install a bypass to reject the disturbance then pair the manipulated and controlled variables in a HEN using NS-RGA (None Square Relative Gain Array) and SVD (Singular Value decomposition), by adopting controllability index developed by Westphalen et al.[4]to measure the HEN controllability and finally a cost tradeoff between the bypass installation and utility installation to control the same disturbance is evaluated to check for the more cost effective method to eliminate and reject the disturbance in hand.

***Keywords:** Controllability, Disturbance propagation, Disturbance rejection, HEN*

I. INTRODUCTION

A Heat exchanger Network (HEN) is considered optimum operational if the following objectives are fulfilled which construct the operability of the HEN:-

1- *Streams target temperatures are achieved.*
2- *Minimization of the net cost.*
3- *Reliability and safety consideration of the HEN.*
4- *Sustainability and Environmental consideration.*
5- *Observability-Controllability and Flexibility considerations- the network is dynamically stable.*

The global optimum solution for a HEN shouldn't be a cost trade off only but should be cost operability trade off. For any process taking into account only economic aspects without considering operability can result into disastrous outcomes.

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For a HEN it is critical to describe the behavior of any disturbance and how it affects streams target temperature and more importantly is how to reduce or eliminate that disturbance. Controllability and flexibility are two important features of a HEN, which describe the disturbance behavior.

and provide the methods to control or/and suppress the deviation in the streams target temperatures[5]. The interconnections among process streams, generate numerous downstream paths through which disturbances propagate. Some of these interconnections should be examined with extra care because intense disturbances might propagate through the paths generated by the interconnections, thereby detrimentally affecting the controllability of the process. This implies that the controllability of a process can be assessed by examining the disturbance propagation in a process structure[6][7].

II. PROBLEM DESCRIPTION

To control the target temperatures for a set of streams in a heat exchanger network the disturbance propagation due to any fluctuation in the inlet parameters in the heat exchangers network need to be evaluated to calculate the deviation in the target streams and construct a control scheme to eliminate that deviation. The following model evaluates the disturbance propagation in a HEN and control the streams outlet temperatures in two major steps the first step is to evaluate and construct a system disturbance propagation model the second step is to construct a control scheme to eliminate the disturbance.

The following assumptions are applied in this work:-

1. No phase change occurs in any heat exchanger
2. Constant heat capacity and constant over all heat transfer coefficient for each heat exchanger.
3. Changes in streams pressure drop is negligible.

The data required are:

1. Heat exchanger network work flow
2. Hot and cold streams data for each unit heat exchanger i.e. (inlet temperatures, outlet temperature and heat capacity flow rate for the streams) and the split ratio for any stream is required in case of splitting between multi-unit heat exchanger.
3. A specified range for uncertainties (inlet temperature, heat capacity flow rates).

The goal here is to evaluate the disturbance propagation through Heat exchanger network, find the effect of changing an inlet parameter for any stream on the other streams even if they are not directly connected and finally systematically construct a control scheme by a tradeoff the cost of the disturbance to the cost of applying the control to the HEN. This research considered the following issues:-

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1. Overall review on controllability of a HEN.
2. Construct a system disturbance model for a HEN.
3. Construct a systematic control scheme to eliminate the disturbance.

III. METHODOLOGY

In this chapter the control of streams outlet temperature is discussed as stated in the previous section the control of streams outlet temperatures can be achieved through two main ways which are the installation of utility heat exchanger in which the excess heat is absorbed or the required heat is added or the second way is to apply a bypass through the heat exchanger. The two methods are discussed and dissected in this department and the cost and the pertinence of the control will define which method will be employed.

The following figure describes a unit heat exchanger with the inlets and the outlets and the bypass configuration.

The following steps are used to evaluate the bypass fraction for each bypass .After the disturbance is evaluated in the previous section the same steps are used yet the bypass fraction is added to eliminate the disturbance in the streams outlet temperatures in the following way.

A. *Unit based disturbance propagation and control Model*

the first step is to Construct unit based disturbance and control model, in the previous section a model for disturbance propagation in heat exchanger networks is developed in which the change in the streams target temperatures are calculated based on the disturbance in the inlet parameters in this case are the inlet streams temperatures and heat capacity flow rate equation describes that model. A new term is added to the model in which bypass fraction changes the streams outlet temperatures in the following manner:-

From heat balance equation and from design equation a HEX with bypass options is sketched in Figure-7. The energy balance and heat-transfer equations can be readily derived, as below. Here, an arithmetic mean-temperature difference is used by neglecting high-order differentiation terms and replacing a logarithmic mean temperature difference by an arithmetic mean term.

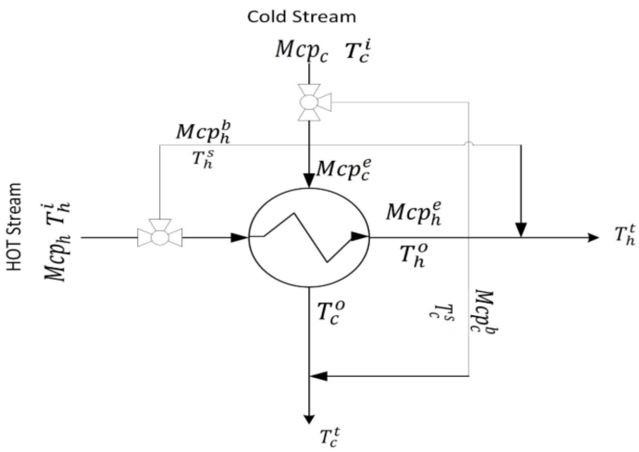

Fig 1 Unit heat exchanger with bypass configuration

This approximation will not introduce any calculation error for stream target temperatures when input temperature disturbances exist, but will cause some prediction errors when mass flow rate disturbances enter the system, the model can be simplified to a linear equation and the conclusion of that model is adop:

$$\delta T^t = B * \delta f + D_t * \delta T^s + D_m * \delta Mcp \ \{1\}$$

Where

$$B = \begin{bmatrix} \dfrac{\alpha(T_h^s - T_h^t)}{2*(1-f_h)^2} & \dfrac{\beta(T_h^s - T_h^t)}{2*(1-f_c)^2} \\ \dfrac{-\alpha(T_c^t - T_c^s)}{2*(1-f_c)^2} & \dfrac{-\beta(T_c^t - T_c^s)}{2*(1-f_c)^2} \end{bmatrix} \{2\}$$

$$D_t = \begin{bmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{bmatrix} \{3\}$$

$$D_m = \begin{bmatrix} \alpha_h(2 - \dfrac{\alpha}{1-f_h}) & -\dfrac{\alpha\,\alpha_c}{1-f_c} \\ \dfrac{\beta\,\alpha_c}{1-f_h} & -\alpha_c(2 - \dfrac{\beta}{1-f_c}) \end{bmatrix} \{4\}$$

$$\alpha = \frac{T_h^s - T_h^t}{T_c^t - T_c^s} \{5\}$$

$$\beta = \frac{T_c^t - T_c^s}{T_h^s - T_c^s} \{6\}$$

$$\alpha_h = \frac{T_h^s - T_h^t}{2Mcp_h} \{7\}$$

$$\alpha_c = \frac{T_c^t - T_c^s}{2Mcp_c} \{8\}$$

Where:-

T_h^i , T_c^i : Inlet temperatures for hot and cold streams respectively.

T_h^o,T_c^o: outlet temperatures from heat exchanger for hot and cold streams respectively.

Mcp_h^e ,Mcp_c^e : fractions of heat capacity flow rate going through heat exchanger for hot and cold streams respectively.

Mcp_h^b ,Mcp_c^b : fractions of heat capacity flow rate going through heat exchanger bypass for hot and cold streams respectively.

T_h^t,T_c^t: outlet temperatures after bypass connection for hot and cold streams respectively.

B. *Heat exchanger bypass availability*

For each heat exchanger f_h^{lim} and f_c^{lim} are calculated to ensure system feasibility after bypass is installed in control scheme If f_h^{lim} and f_c^{lim} equal zero should be eliminated in control scheme as in that case there will violation for ΔT_{min} .

The relation between the bypass fraction and ΔT_{min} is concluded as follows:-

The following relation must be obtained to ensure system feasibility

$$T_h^i - T_c^o \geq \Delta T_{min} \{9\}$$

$$T_h^o - T_c^i \geq \Delta T_{min} \{10\}$$

$$T_h^i - T_c^o = T_h^s - T_c^o \{11\}$$

$$T_h^o - T_c^s = T_h^o - T_c^s \{12\}$$

For the bypass placed on the hot side of the heat exchanger

$$T_h^t = f_h T_h^s + (1 - f_h) T_h^o \{12\}$$

Similarly for the cold stream bypass

$$T_c^t = f_c T_c^s + (1 - f_c) T_c^o \{13\}$$

Substituting equation (13), (12) into equations (11), (10)

$$T_h^t - T_c^s - \Delta T_{min} \geq f_h (T_h^s - T_c^s - \Delta T_{min}) \{14\}$$

Since the term $T_h^s - T_c^s - \Delta T_{min}$ is definitely positive

$$f_h \leq \frac{T_h^t - T_c^s - \Delta T_{min}}{T_h^s - T_c^s - \Delta T_{min}} \{15\}$$

So the upper limit of nominal fraction of the bypass placed on the hot stream side of Heat exchanger

$$f_h^{lim} = \frac{T_{h_{Ei}}^t - T_{c_{Ei}}^s - \Delta T_{min}}{T_{h_{Ei}}^s - T_{c_{Ei}}^s - \Delta T_{min}} \{16\}$$

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Similarly, for the cold stream of the heat exchanger;

$$f_c^{lim} = \frac{T_{h_{Ei}}^{s} - T_{c_{Ei}}^{t} - \Delta T_{min}}{T_{h_{Ei}}^{s} - T_{c_{Ei}}^{s} - \Delta T_{min}} \{17\}$$

Where:

f_h^{lim}, f_c^{lim}: are the hot and cold streams available bypass fractions.

These relations can be stated as follows:

$0 \le f_h \le f_h^{lim}$ {18}

$0 \le f_c \le f_c^{lim}$ {19}

By applying these relations to design equation-

Where $Q = UA\Delta T_{lmtd}$ SO

$$A\Delta T_{lmtd} = \frac{Q}{U} \{20\}$$

And at constant U and Q the term Q/U is always positive, from equation

$$T_h^t = f_h T_h^s + (1 - f_h) T_h^o \{21\}$$

Then

$$T_h^o = \frac{T_h^t - f_h T_h^s}{(1 - f_h)} \{22\}$$

$$\Delta T_{lmin} = \frac{(T_h^s - T_c^o) - (T_h^o - T_c^s)}{\ln \dfrac{(T_h^s - T_c^o)}{(T_h^o - T_c^s)}} \{23\}$$

Substituting equation (22) into equation (23)

$$\Delta T_{lmin} = \frac{(T_h^s - T_c^o) - \left(\dfrac{T_h^t - f_h T_h^s}{(1 - f_h)} - T_c^s\right)}{ln \dfrac{(T_h^s - T_c^o)}{\left(\dfrac{T_h^t - f_h T_h^s}{(1 - f_h)} - T_c^s\right)}} \{24\}$$

Similarly for placing the bypass at the cold side of the heat exchanger

$$T_c^o = \frac{T_c^t - f_c T_c^s}{(1 - f_c)} \{25\}$$

$$\Delta T_{lmin} = \frac{\left(T_h^s - \dfrac{T_c^t - f_c T_c^s}{(1 - f_c)}\right) - (T_h^o - T_c^s)}{\ln \dfrac{\left(T_h^s - \dfrac{T_c^t - f_c T_c^s}{(1 - f_c)}\right)}{(T_h^o - T_c^s)}} \{26\}$$

By changing f_h affect ΔT_{lmin} so the HEX area must be changed to maintain constant Q.

$A^* \Delta T_{lmin} = A^{new} * \Delta T_{lmin}^{new}$ {27}

So $A^{new} = A \frac{\Delta T_{lmin}}{\Delta T_{lmin}^{new}}$ {28}

C. *System disturbance and propagation model*

System topology matrices are first constructed which describe the propagation of the disturbance through the Hen either inlet temperature disturbance or heat capacity flow rate disturbance through system topology the derivation of the system matrices V1,V2,V3 and V4 are well explained by Yang et al.

The equation which describes the system disturbance and control as follows:

$$\delta T^t = B * \delta f + D_t * \delta T^s + D_m * \delta MCP \{29\}$$

$$\begin{bmatrix} \delta T_h^t \\ \delta T_c^t \end{bmatrix} = B * \delta f + [D_{th} \quad D_{tc}] * \begin{bmatrix} \delta T_h^s \\ \delta T_c^s \end{bmatrix} + [D_{mh} \quad D_{mc}] * \begin{bmatrix} \delta MCP_h \\ \delta MCP_c \end{bmatrix} \{30\}$$

Where

$$B = B_1 + D_{t12} * (I - D_{t22})^{-1} * B_2 \{31\}$$

$$D_t = D_{t11} + D_{t12} * (I - D_{t22})^{-1} * D_{t22} = (D_{th}^T \ D_{tc}^T)^T \{32\}$$

$$D_m = D_{m1} + D_{t12} * (I - D_{t22})^{-1} * D_{m1} = (D_{mh}^T \ D_{mc}^T)^T \{33\}$$

$$\delta T_h^t = (\delta T_{h1}^t \ \delta T_{h2}^t \ \delta T_{h3}^t \ \dots \dots . \delta T_{hN_h}^t)^T \{34\}$$

$$\delta T_c^t = (\delta T_{c1}^t \ \delta T_{c2}^t \ \delta T_{c3}^t \ \dots \dots . \delta T_{cN_c}^t)^T \{35\}$$

$$\delta f = ((\delta f)_{E1}^T \ (\delta f)_{E2}^T (\delta f)_{E3}^T \dots . . (\delta f)_{Ne}^T)^T \{36\}$$

$$\delta T_h^s = (\delta T_{h1}^s \ \delta T_{h2}^s \ \delta T_{h3}^s \ \dots \dots . \delta T_{hN_h}^s)^T \{37\}$$

$$\delta T_c^s = (\delta T_{c1}^s \ \delta T_{c2}^s \ \delta T_{c3}^s \ \dots \dots . \delta T_{cN_c}^s)^T \{38\}$$

$$\delta MCP_h = \left(\delta MCP_{h1} \delta MCP_{h2} \delta MCP_{h3} \dots \dots \delta MCP_{N_h}\right)^T \{39\}$$

$$\delta MCP_c = \left(\delta MCP_{c1} \delta MCP_{c2} \delta MCP_{c3} \dots \dots \delta MCP_{N_c}\right)^T \{40\}$$

D. *Bypass placing procedures*

To construct a HEN with best by pass placing RGA is used[8]. But in this case regular RGA cannot be calculated as the gain matrix (K) which in our design is (B) as our manipulated variables are the bypass fraction and our controlled variables are the streams target temperatures so

$$RGA = B \otimes (B^{-1})^T \{41\}$$

Where $\otimes$ is element by element multiplication operator.

And because B is not a square matrix so extended relative gain array RGA^e is obtained Using Nobel and Daniel theorems

$$RGA^e = B \otimes (B^*)^T \{42\}$$

Where B^* is the pseudoinverse of B to calculate B*

$$B^* = V * (\Sigma^*) * U^T \{43\}$$

Where

*Σ** is pseudoinverse of singular matrix *(Σ)* for control matrix *(B)*

V and U are the unitary matrices for singular decomposition of matrix *(B)*

U^T is the transpose of U.

Applying the singular decomposition analysis is:-

$$SVD(B) = [U \Sigma V] \{44\}$$

The RGA^e can represent the best pairing between the controlled and manipulated variables

After concluding the RGA^e we can use the pairing rules for RGA are as follow:

1) RGA pairing rules:

1-f_h^{lim} and f_c^{lim} validation for feasibility

- Calculate $f_h^{lim} = \frac{Tth - Tsc - \Delta Tmin}{Tsh - Tsc - \Delta Tmin}$ {45}
- Calculate $f_c^{lim} = \frac{Tsh - Ttc - \Delta Tmin}{Ths - Tsh - \Delta Tmin}$ {46}

Where f_h^{lim} and f_c^{lim} are the maximum allowable by pass fractions can a unit a heat exchanger tolerate without validation the network feasibility (ΔT_{min}).

For f_h^{lim} and f_c^{lim} =0 the bypass should eliminated as a manipulated variable.

2-For the same heat exchanger f_c^{lim} and f_c^{lim} the greater value should be used as a manipulated variable for the respective controlled variable if they their respective RGA have the same condition number.

3-For the same heat exchanger if it is the only available manipulated variable for the cold and hot streams:-

- It should be used as manipulated variable for the stream must be controlled from process point of view.
- If no stream have no importance to be controlled over the other stream it should be used as a manipulating variable for the stream which have no utility heat exchanger.

- If no above conditions is applied refer to number 1 rule.

4-Utility heat exchanger shouldn't be used as a manipulated variable only after investigating RGA and find no process heat exchanger available for the same controlled stream.
5-For RGA pairing rule

- Pairing with λ_{ij} element with value $\cong 1$ should be used
- Pairing with λ_{ij} element with value ≤ 0 should be eliminated.
- The interpretation of the elements (λ_{ij}) can be stated as follows:-

1. For $\lambda_{ij} = 1.0$, there is no interaction with other control loops, and the pairing i—j should be used.
2. For $\lambda_{ij} = 0$, manipulated variable j has no effect on controlled variable i.
3. For $\lambda_{ij} = 0.5$, there is a high degree of interaction with other control loops.
4. For $0.5 < \lambda_{ij} < 1.0$, there is interaction with other control loops; however, the i—j pairing would be preferable as it would minimize interactions.
5. For $\lambda_{ij} > 1.0$, the interaction with other loops reduces the effect of the control loop.
6. For $\lambda_{ij} < 0.0$, the pairing i—j might lead to an unstable operation.

After applying the above rules if we have more than one set condition number should be used as a robustness measure The set have the lowest condition number should be used as it is will conditioned. Condition number as a robustness measure: Although RGA gives a good indication of pairing controlled and manipulated variables it gives no indication for the condition of pairings so condition number is used.

2) Condition number as a measure of controllability

Condition number of a matrix Is the ratio of the largest singular value of that matrix to the smallest singular value The P-norm condition number of the matrix A is defined as norm (A, P)*norm (inverse (A), P), where norm is the norm of the matrix A. Where the norm of matrix A is the raw sum norm, which defined as

$$\|A\|_\infty = \max_{1\leq i\leq m} \sum_{j-1}^{n} |a_{ij}| \quad \{47\}$$

The condition number and RGA are used both to measure interaction in multivariate systems .If the condition number of system is large, the system will be ill-condition and such a system will be difficult to control. But it does not mean that the system has high interaction, because an ill-condition system does not necessarily have large RGA elements. Being high the condition number is caused by various factors, but only in the case that it is due to large RGA elements, it could be concluded that the system has high interaction. So, if RGA elements are large, condition number of system will be high (ill-condition system) and the interaction will also be high. Also if a system has high interaction, then the system has large RGA elements and will be ill-condition[4][8].

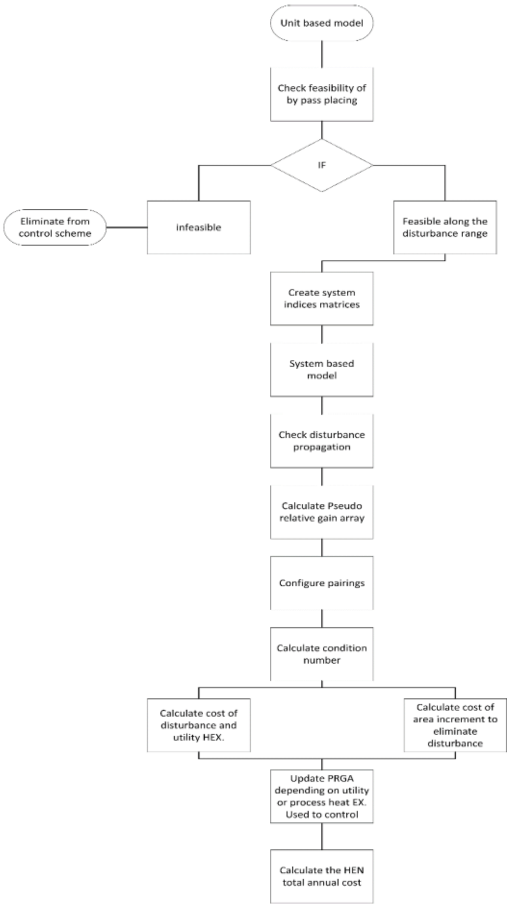

Fig 2 Methodology summary block diagram

E. *Calculating temperature deviation cost*

To calculate the cost earned by eliminating this deviation the following equation is used

$$DC = Mcp_i * \delta T_i^t * (UC) * \varepsilon + \varphi \ \{48\}$$

Where:

ε: Is the probability of the disturbance per year for convenience ε=1 for the greater disturbance impact.

φ:Is the impact of the change in the stream target temperature on the whole process for convenience φ=0$.

The methodology used in this work proven reliability and precedence by shown the ability to reproduce the results in three different cases variant in complexity and checked for feasibility and the ability to reject disturbance and show good controllability characteristics with cost optimization[9].

Fig-2 summarizes the methodology used in this work.

IV. CASE STUDIES.

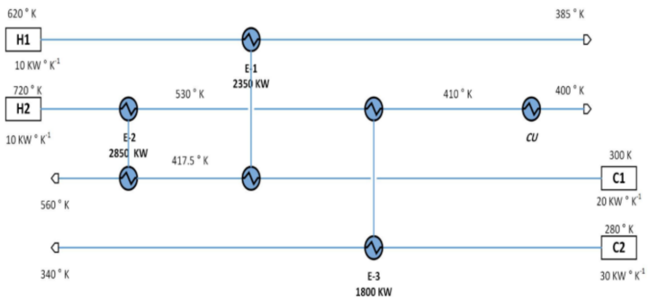

Fig 3 Four strams case study

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A systematic approach is derived for the above four stream HEN showed in figure (3) which was studied by Linnhoff et al (1982), Yee and Grossman (1990), D. Uzturk and U. Akman(1997) and Y.L.Huang and Y.H.Yang (2001).Steady state design data are listed in (Table I)[2][10].

Table I Case study steady state data

Stream	Inlet temp(°K)	outlet temp(°K)	Heat capacity flow rate(KW°K^{-1})
H1	620	385	10
H2	720	400	15
C1	300	560	20
C2	280	340	30

U=0.5 Kw m^{-2}K^{-1} $\Delta T_{min} = 10°K$

Original heat exchangers area (A): E1=34.7 m^2, E2=42.3 m^2 and E3=22.8 m^2

Cost of heating utility=80 \$/Kw year

Cost of cooling utility=20 \$/Kw year

Annual fixed cost=1000 A$^{0.6}$ (area m^2) \$/year

In this case by using bypass and utility heat exchangers a control scheme is developed so that any disturbance in the inlet parameters can rejected. Using bypass or utility heat exchangers depend on a tradeoff between the cost of the disturbance and the cost of installing bypass or utility heat exchanger to achieve that final scheme the following steps are applied.

First step

Drive system topology matrices which are well described in the previous chapter.

$$S=\begin{array}{c c} & \begin{matrix} \begin{bmatrix} E1 \\ h\ c \end{bmatrix} & \begin{bmatrix} E2 \\ h\ c \end{bmatrix} & \begin{bmatrix} E3 \\ h\ c \end{bmatrix} \end{matrix} \\ \begin{bmatrix} H1 \\ H2 \\ C1 \\ C2 \\ m1 \\ m2 \end{bmatrix} & \begin{bmatrix} 1\,0 & 0\,0 & 0\,0 \\ 0\,0 & 1\,0 & 1\,0 \\ 0\,1 & 0\,1 & 0\,0 \\ 0\,0 & 0\,0 & 0\,1 \\ 0\,0 & l\,0 & e\,0 \\ 0\,l & 0\,e & 0\,0 \end{bmatrix} \end{array}$$

Drive matrices V1, V2 and V3

$$V1=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$V2=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

$$V3=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Before identifying the suitable bypass to be installed V4 matrix which represent the candidate bypass to be installed are set to unity matrix with dimensions of ($2{*}N_e$; $2{*}N_e$) where each heat exchanger have two sides (i.e. two possibilities to place the bypass) hot and cold streams.

$$\text{So } V4=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Second step

Construct unit based disturbance propagation and control model and check the bypass availability, for each heat exchanger the model in eqution-1221 is calculated and the condition explained in equations 10 to 15 are checked to confirm the bypass availability

For heat exchanger E-1

Table II Heat exchanger E-1 steady state data

Inlet streams	Inlet temp. K°	Target temp. K°	Mcp KW K°$^{-1}$
Hot stream(H1)	620	385	10
Cold stream(C1)	300	417.5	30

For each unit heat exchanger the model described in equation is constructed using equations (4.17 to 4.24) as follows:

$$\alpha = \frac{T_h^s - T_h^t}{T_c^t - T_c^s} = \frac{620-385}{417.5-300} = 0.7344$$

$$\beta = \frac{T_c^t - T_c^s}{T_h^s - T_c^s} = \frac{417.5-300}{620-300} = 0.3672$$

$$\alpha_h = \frac{T_h^s - T_h^t}{2Mcp_h} = \frac{620-385}{2*10} = 11.75$$

$$\alpha_c = \frac{T_c^t - T_c^s}{2Mcp_c} = \frac{417.5-300}{2*20} = 9.5$$

So

$$B = \begin{bmatrix} \frac{\alpha(T_h^s - T_h^t)}{2*(1-f_h)^2} & \frac{\beta(T_h^s - T_h^t)}{2*(1-f_c)^2} \\ \frac{-\alpha(T_c^t - T_c^s)}{2*(1-f_c)^2} & \frac{-\beta(T_c^t - T_c^s)}{2*(1-f_c)^2} \end{bmatrix} = \begin{bmatrix} 86.2891 & 43.1445 \\ -43.1445 & -21.5723 \end{bmatrix}$$

$$D_t = \begin{bmatrix} 1-\alpha & \alpha \\ \beta & 1-\beta \end{bmatrix} = \begin{bmatrix} 0.2656 & 0.7344 \\ 0.3672 & 0.6328 \end{bmatrix}$$

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$$D_m = \begin{bmatrix} \alpha_h(2-\frac{\alpha}{1-f_h}) & -\frac{\alpha\alpha_c}{1-f_c} \\ \frac{\beta\alpha_c}{1-f_h} & -\alpha_c(2-\frac{\beta}{1-f_c}) \end{bmatrix} = \begin{bmatrix} 14.8711 & -21.5720 \\ 4.3145 & -4.7964 \end{bmatrix}$$

So the unit based model of disturbance propagation and control for Heat exchanger E-1 is:

$$\begin{bmatrix} \delta T^t_{H1} \\ \delta T_{m2} \end{bmatrix} = \begin{bmatrix} 86.2891 & 43.1445 \\ -43.1445 & -21.5723 \end{bmatrix} \begin{bmatrix} \delta f^{E1}_{H1} \\ \delta f^{E1}_{C1} \end{bmatrix} + \begin{bmatrix} 0.2656 & 0.7344 \\ 0.3672 & 0.6328 \end{bmatrix} \begin{bmatrix} \delta T^s_{H1} \\ \delta T^s_{C1} \end{bmatrix} + \begin{bmatrix} 14.8711 & -21.5720 \\ 4.3145 & -4.7964 \end{bmatrix} \begin{bmatrix} \delta Mcp_{H1} \\ \delta Mcp_{C1} \end{bmatrix} \; ()$$

Checking bypass availability:-

Using equations (4.35) (4.36) the bypass availability is checked:

$$f_h^{lim} = \frac{T^t_{h_{E1}} - T^s_{c_{E1}} - \Delta T_{min}}{T^s_{h_{E1}} - T^s_{c_{E1}} - \Delta T_{min}} = \frac{417.5 - 300 - 10}{620 - 300 - 10} = 0.2419$$

$$f_c^{lim} = \frac{T^s_{h_{E1}} - T^t_{c_{E1}} - \Delta T_{min}}{T^s_{h_{E1}} - T^s_{c_{E1}} - \Delta T_{min}} = \frac{583 - 389.6667 - 10}{583 - 313 - 10} = 0.7051$$

So as f_h^{lim} and f_c^{lim} are not zeros no bypass is eliminated from the control scheme.

Applying the relation between the bypass fraction and heat exchanger area and plotting a graph between the bypass fraction for cold and hot streams and area, that relation can be used to calculate the increment of the cost due to the change in the heat exchanger from the HEN area cost annualization equation.

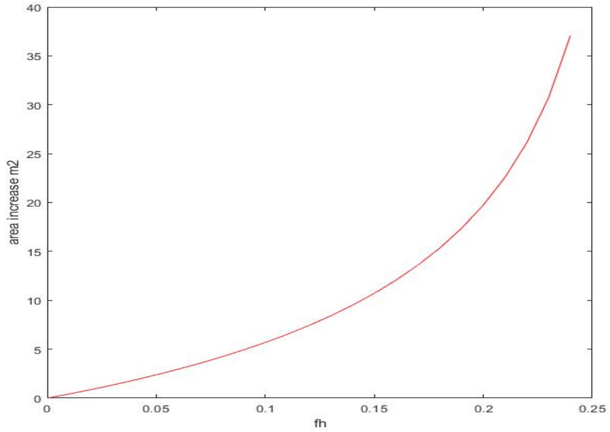

Fig 4 Area increase in Heat exchanger E-1 for increasing hot side bypass fraction

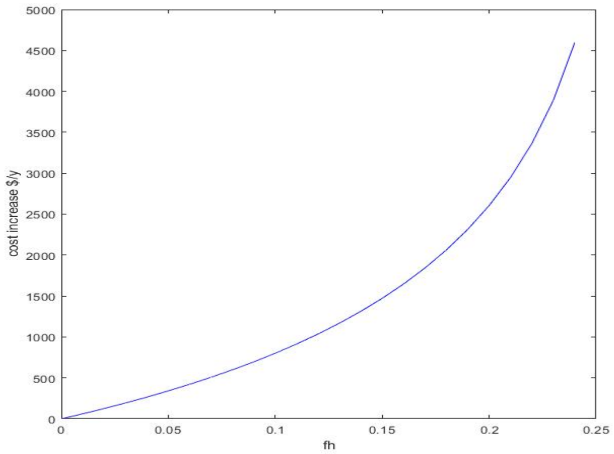

Fig 5 Cost increase in Heat exchanger E-1 for increasing hot side bypass fraction

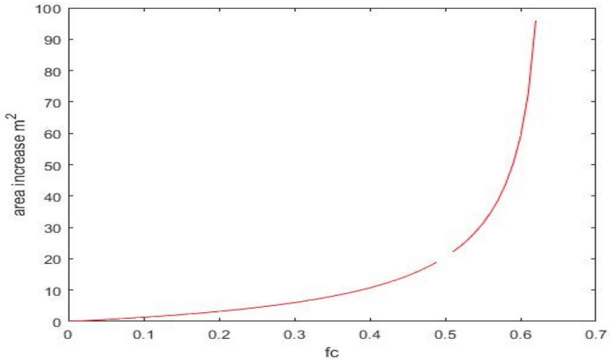

Fig 6 Area increase in Heat exchanger E-1 for increasing cold side bypass fraction

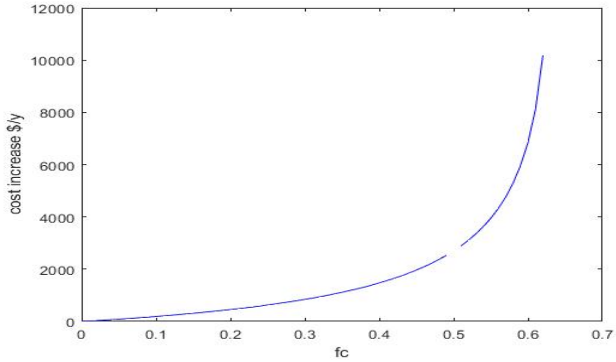

Fig 7Cost increase in Heat exchanger E-1 for increasing cold side bypass fraction

Similarly the same steps are applied to HEX-2 and HEX-3:-

Heat exchanger E-2

Table III Heat exchanger E-2 Steady state data

Inlet streams	Inlet temp. K°	Target temp. K°	Mcp KW K°-1
Hot stream(H2)	720	530	10
Cold stream(C1)	417.5	560	20

Area=42.3 m²

$\alpha = 0.6281$

$\beta = 0.4711$

$\alpha_h = 9.5$

$\alpha_c = 3.5625$

$$B = \begin{bmatrix} 59.6694 & 44.7521 \\ -44.7521 & -33.5640 \end{bmatrix}$$

$$D_t = \begin{bmatrix} 0.3719 & 0.6281 \\ 0.4711 & 0.5289 \end{bmatrix}$$

$$D_m = \begin{bmatrix} 13.0331 & -2.2376 \\ 4.4752 & -5.4468 \end{bmatrix}$$

The unit disturbance propagation and control for E-2:-

$$\begin{bmatrix} \delta T_{m1} \\ \delta T^t_{C1} \end{bmatrix} = \begin{bmatrix} 59.6694 & 44.7521 \\ -44.7521 & -33.5640 \end{bmatrix} \begin{bmatrix} \delta f^{E2}_{H2} \\ \delta f^{E2}_{C1} \end{bmatrix} + \begin{bmatrix} 0.3719 & 0.6281 \\ 0.4711 & 0.5289 \end{bmatrix} \begin{bmatrix} \delta T^s_{H2} \\ \delta T_{m2} \end{bmatrix} + \begin{bmatrix} 13.0331 & -2.2376 \\ 4.4752 & -5.4468 \end{bmatrix} \begin{bmatrix} \delta Mcp_{H2} \\ \delta Mcp_{C1} \end{bmatrix}$$

Checking bypass availability:-

$$f_{hE2}^{lim} = \frac{T^t_{h_{E2}} - T^s_{c_{E2}} - \Delta T_{min}}{T^s_{h_{E2}} - T^s_{c_{E2}} - \Delta T_{min}} = \frac{530 - 417.5 - 10}{720 - 417.5 - 10} = 0.3504$$

$$f_{cE2}^{lim} = \frac{T^s_{h_{E2}} - T^t_{c_{E2}} - \Delta T_{min}}{T^s_{h_{E2}} - T^s_{c_{E2}} - \Delta T_{min}} = \frac{720 - 560 - 10}{720 - 417.5 - 10} = 0.5128$$

So as f_h^{lim} and f_c^{lim} are not zeros no bypass is eliminated from the control scheme.

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Applying the relation between the bypass fraction and heat exchanger area and plotting a graph between the bypass fraction for cold and hot streams and area

We can use that relation to calculate the increment of the cost due to the change in the heat exchanger from the HEN area cost annualization equation as previously explained in Heat exchanger E-1.

Heat exchanger E-3

Table IV Heat exchanger E-3 steady state data

Inlet streams	Inlet temp. K°	Target temp. K°	Mcp KW K°-1
Hot stream(H2)	530	410	10
Cold stream(C2)	280	340	30

Area=22.8 m^2

$\alpha = 0.4800$

$\beta = 0.2400$

$\alpha_h = 6$

$\alpha_c = 1$

$$B = \begin{bmatrix} 28.8000 & 14.4000 \\ -14.4000 & -7.2000 \end{bmatrix}$$

$$D_t = \begin{bmatrix} 0.5200 & 0.4800 \\ 0.2400 & 0.7600 \end{bmatrix}$$

$$D_m = \begin{bmatrix} 9.1200 & -0.4800 \\ 1.4400 & -1.7600 \end{bmatrix}$$

The unit disturbance propagation and control for E-3:-

$$\begin{bmatrix} \delta T_{H2}^t \\ \delta T_{C2}^t \end{bmatrix} = \begin{bmatrix} 28.8000 & 14.4000 \\ -14.4000 & -7.2000 \end{bmatrix} \begin{bmatrix} \delta f_{H2}^{E3} \\ \delta f_{C2}^{E3} \end{bmatrix} + \begin{bmatrix} 0.5200 & 0.4800 \\ 0.2400 & 0.7600 \end{bmatrix} \begin{bmatrix} \delta T_{m1} \\ \delta T_{C2}^s \end{bmatrix} + \begin{bmatrix} 9.1200 & -0.4800 \\ 1.4400 & -1.7600 \end{bmatrix} \begin{bmatrix} \delta Mcp_{H2} \\ \delta Mcp_{C2} \end{bmatrix}$$

Checking bypass availability:-

$$f_{hE3}^{lim} = \frac{T_{h_{E3}}^t - T_{c_{E3}}^s - \Delta T_{min}}{T_{h_{E3}}^s - T_{c_{E3}}^s - \Delta T_{min}} = \frac{410 - 280 - 10}{530 - 280 - 10} = 0.5000$$

$$f_{cE3}^{lim} = \frac{T_{h_{E3}}^s - T_{c_{E3}}^t - \Delta T_{min}}{T_{h_{E3}}^s - T_{c_{E3}}^s - \Delta T_{min}} = \frac{530 - 340 - 10}{530 - 280 - 10} = 0.7500$$

So as f_h^{lim} and f_c^{lim} are not zeros no bypass is eliminated from the control scheme.

The next step is to construct system disturbance and control model explained in equations (4.59).

$$D_{tE}^* = \begin{bmatrix} 0.2656 & 0.7344 & 0 & 0 & 0 & 0 \\ 0.3672 & 0.6328 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.3719 & 0.6281 & 0 & 0 \\ 0 & 0 & 0.4711 & 0.5289 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.5200 & 0.4800 \\ 0 & 0 & 0 & 0 & 0.2400 & 0.7600 \end{bmatrix}$$

So

$$D_t^* = \begin{bmatrix} 0.2656 & 0 & 0.7344 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.4800 & 0.5200 & 0 \\ 0 & 0.4711 & 0 & 0 & 0 & 0.5289 \\ 0 & 0 & 0 & 0.7600 & 0.2400 & 0 \\ 0 & 0.3719 & 0 & 0 & 0 & 0.6281 \\ 0.3672 & 0 & 0.6328 & 0 & 0 & 0 \end{bmatrix}$$

$$D_{ME}^* = \begin{bmatrix} 14.8711 & -21.5720 & 0 & 0 & 0 & 0 \\ 4.3145 & -4.7964 & 0 & 0 & 0 & 0 \\ 0 & 0 & 13.0331 & -2.2376 & 0 & 0 \\ 0 & 0 & 4.4752 & -5.4468 & 0 & 0 \\ 0 & 0 & 0 & 0 & 9.1200 & -0.4800 \\ 0 & 0 & 0 & 0 & 1.4400 & -1.7600 \end{bmatrix}$$

$$D_m^* = \begin{bmatrix} 14.8711 & 0 & -2.1572 & 0 \\ 0 & 9.12 & 0 & -0.4800 \\ 0 & 4.4752 & -5.4468 & 0 \\ 0 & 1.4400 & 0 & -1.7600 \\ 0 & 13.0331 & -2.2376 & 0 \\ 4.3145 & 0 & -4.7964 & 0 \end{bmatrix}$$

$$B_E^* = \begin{bmatrix} 86.2891 & 43.1445 & 0 & 0 & 0 & 0 \\ -43.1445 & -21.5723 & 0 & 0 & 0 & 0 \\ 0 & 0 & 59.6694 & 44.7521 & 0 & 0 \\ 0 & 0 & -44.7521 & -33.5640 & 0 & 0 \\ 0 & 0 & 0 & 0 & 28.8 & -14.4 \\ 0 & 0 & 0 & 0 & -14.4 & -7.2 \end{bmatrix}$$

$$B^* = \begin{bmatrix} 86.2891 & 43.1445 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 28.8 & 14.4 \\ 0 & 0 & -44.7521 & -33.5640 & 0 & 0 \\ 0 & 0 & 0 & 0 & -14.4 & -7.2 \\ 0 & 0 & 59.6694 & 44.7521 & 0 & 0 \\ -43.1445 & -21.5723 & 0 & 0 & 0 & 0 \end{bmatrix}$$

By applying equations (4.53-4.58) we can obtain the model described in equation (4.59) HEN disturbance propagation and control model:-

For the HEN in hand we can construct DP&C model as stated in equation (4.59).

$$\delta T^t = B * \delta f + D_t * \delta T^s + D_m * \delta MCP$$

Using the concluded terms (B, D_t and D_m)

$$\begin{bmatrix} \delta T_{H1}^t \\ \delta T_{H2}^t \\ \delta T_{C1}^t \\ \delta T_{C2}^t \end{bmatrix} = \begin{bmatrix} 86.2891 & 43.1445 & 0 & 0 & 0 & 0 \\ -14.0915 & -7.0458 & 31.0281 & 23.2711 & 28.8 & 14.4 \\ -22.8202 & -11.4101 & -44.7521 & -33.5640 & 0 & 0 \\ -6.5038 & -3.2519 & 14.3207 & 10.7405 & -14.4 & -7.2 \end{bmatrix} * \begin{bmatrix} \delta f_{h1}^{E1} \\ \delta f_{c1}^{E1} \\ \delta f_{h2}^{E2} \\ \delta f_{c1}^{E2} \\ \delta f_{h2}^{E3} \\ \delta f_{c2}^{E3} \end{bmatrix}$$

$$+ \begin{bmatrix} 0.2656 & 0 & 0.7344 & 0 \\ 0.1199 & 0.1934 & 0.2067 & 0.4800 \\ 0.1942 & 0.4711 & 0.3347 & 0 \\ 0 & 0.0893 & 0.0954 & 0.7600 \end{bmatrix} * \begin{bmatrix} \delta T_{H1}^s \\ \delta T_{H2}^s \\ \delta T_{C1}^s \\ \delta T_{C2}^s \end{bmatrix} + \begin{bmatrix} 14.8711 & 0 & -2.1572 & 0 \\ 1.4092 & 15.8972 & -2.7301 & -0.4800 \\ 2.2820 & 4.4752 & -7.9837 & 0 \\ 0.6504 & 4.5679 & -1.2601 & -1.7600 \end{bmatrix}$$

$$* \begin{bmatrix} \delta MCP_{H1} \\ \delta MCP_{H2} \\ \delta MCP_{C1} \\ \delta MCP_{C2} \end{bmatrix}$$

HEN disturbance propagation model:-

To evaluate the deviation in target temperatures due to any disturbance in inlet temperatures or in heat flow rates the following equation is used:-

$$\begin{bmatrix} \delta T_{H1}^t \\ \delta T_{H2}^t \\ \delta T_{C1}^t \\ \delta T_{C2}^t \end{bmatrix} = \begin{bmatrix} 0.2656 & 0 & 0.7344 & 0 \\ 0.1199 & 0.1934 & 0.2067 & 0.4800 \\ 0.1942 & 0.4711 & 0.3347 & 0 \\ 0 & 0.0893 & 0.0954 & 0.7600 \end{bmatrix} * \begin{bmatrix} \delta T_{H1}^s \\ \delta T_{H2}^s \\ \delta T_{C1}^s \\ \delta T_{C2}^s \end{bmatrix} + \begin{bmatrix} 14.8711 & 0 & -2.1572 & 0 \\ 1.4092 & 15.8972 & -2.7301 & -0.4800 \\ 2.2820 & 4.4752 & -7.9837 & 0 \\ 0.6504 & 4.5679 & -1.2601 & -1.7600 \end{bmatrix} * \begin{bmatrix} \delta MCP_{H1} \\ \delta MCP_{H2} \\ \delta MCP_{C1} \\ \delta MCP_{C2} \end{bmatrix}$$

This model can be used to predict the variation in the streams outlet temperatures as the disturbance occur in the streams inlet variables as shown in the previous chapter.

The next step is to find the best bypass placing to control the streams target temperatures. Using the procedures explained in step three the following is concluded:

The gain matrix

$$B = \begin{bmatrix} 86.2891 & 43.1445 & 0 & 0 & 0 & 0 \\ -14.0915 & -7.0458 & 31.0281 & 23.2711 & 28.8 & 14.4 \\ -22.8202 & -11.4101 & -44.7521 & -33.5640 & 0 & 0 \\ -6.5038 & -3.2519 & 14.3207 & 10.7405 & -14.4 & -7.2 \end{bmatrix}$$

And by applying singular value decomposition to matrix B the matrix is decomposed into the following

$SVD(B) = [U\,\Sigma\,V]$

$$U = \begin{bmatrix} -0.9407 & 0.1473 & -0.1783 & 0.22481 \\ 0.1171 & -0.6582 & -0.6439 & 0.3721 \\ 0.3151 & 0.7121 & -0.3839 & 0.4961 \\ 0.0449 & -0.1948 & 0.6373 & 0.7442 \end{bmatrix}$$

$$\Sigma = \begin{bmatrix} 101.7572 & 0 & 0 & 0 & 0 & 0 \\ 0 & 71.6097 & 0 & 0 & 0 & 0 \\ 0 & 0 & 32.0442 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1.3219e^{-15} & 0 & 0 \end{bmatrix}$$

$$V = \begin{bmatrix} -0.8875 & 0.0978 & -0.0530 & -0.1366 & 0.3809 & 0.1904 \\ -0.4437 & 0.0489 & -0.0265 & 0.2733 & -0.7617 & -0.3809 \\ -0.0966 & -0.7692 & 0.1976 & 0.5713 & 0.1640 & 0.0820 \\ -0.0724 & -0.5769 & 0.1482 & -0.7617 & -0.2186 & -0.1093 \\ 0.0268 & -0.2256 & -0.8651 & -0.0001 & 0.2000 & -0.4000 \\ 0.0134 & -0.1128 & -0.4326 & -0.0001 & -0.4000 & 0.8000 \end{bmatrix}$$

So the pseudo inverse of B is $B^* = V * (\Sigma^*) * U^T$

Where U^T is the transpose of U and Σ^* is the pseudo inverse of Σ and because the fourth singular element is so small compared to other elements the fourth element is neglected

$$\text{which yields } \Sigma^* = \begin{bmatrix} 0.0098 & 0 & 0 & 0 \\ 0 & 0.0140 & 0 & 0 \\ 0 & 0 & 0.0312 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\text{So } B^* = \begin{bmatrix} 0.0087 & -0.0009 & -0.0011 & -0.0017 \\ 0.0044 & -0.0004 & -0.0006 & -0.0009 \\ -0.0018 & 0.0030 & -0.0103 & 0.0060 \\ -0.0013 & 0.0022 & -0.0077 & 0.0045 \\ 0.0041 & 0.0195 & 0.0082 & -0.0166 \\ 0.0021 & 0.0097 & 0.0041 & -0.0083 \end{bmatrix}$$

The extended relative gain array

$$RGA^e = B \otimes (B^*)^T = \begin{bmatrix} 0.7508 & 0.1877 & 0 & 0 & 0 & 0 \\ 0.0121 & 0.0030 & 0.0928 & 0.0522 & 0.5612 & 0.1403 \\ 0.0260 & 0.0065 & 0.4616 & 0.2597 & 0 & 0 \\ 0.0111 & 0.0028 & 0.0856 & 0.0482 & 0.2388 & 0.0597 \end{bmatrix}$$

Using the pairing rules explained in the previous section yields the following results:

1-Stream H1 is paired with heat exchanger E-1 hot side.
2-Stream H2 is paired with heat exchanger E-3 cold side.
3-Stream C1 is paired with heat exchanger E-2 hot side.

As previously stated each unit can be used to control one manipulated variable so we can find that stream C2 can't be controlled using utility heat exchanger as it has the lowest pairing value.

After the pairings were identified the remaining manipulated variables are removed from the control scheme reducing the gain matrix B relative gain array RGA^e as follows:

$$\begin{bmatrix} \delta T_{H1}^t \\ \delta T_{H2}^t \\ \delta T_{C1}^t \\ \delta T_{C2}^t \end{bmatrix} = \begin{bmatrix} 86.2891 & 0 & 0 \\ -14.0915 & 31.0281 & 14.4 \\ -22.8202 & -44.7521 & 0 \\ -6.5038 & 14.3207 & -7.2 \end{bmatrix} * \begin{bmatrix} \delta f_{h1}^{E1} \\ \delta f_{h2}^{E2} \\ \delta f_{c2}^{E3} \end{bmatrix}$$

$$RGA^r = \begin{bmatrix} 0.9385 & 0 & 0 \\ 0.0151 & 0.1449 & 0.7015 \\ 0.0325 & 0.7213 & 0 \\ 0.0139 & 0.1338 & 0.2985 \end{bmatrix}$$

The condition number is then calculated to measure the robustness of the system. The condition number for the system before modification $7.6973e^{16}$ and the condition after modification is 6.2186 meaning the system is more robust.

The next step is to calculate the optimum bypass fraction by applying changes to the bypass selection matrix V4 reducing V4 to

$$V4 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

From that changes applied to the system disturbance and propagation model and apply a fraction to the originally zero bypass fraction and compare the cost added value (area increase of the unit heat exchanger) to the cost of disturbance For each bypass set as the manipulated variable to control the controlled variable the stream target temperature- a tradeoff between the cost of the bypass installment and the cost of maximum disturbance can be eliminated by the nominal bypass fraction is plotted to determine the optimum nominal fraction or using utility heat exchanger is more economical than increasing the heat exchanger area.

A. *Target temperature of stream H1 using heat exchanger E1 hot side.*

A range of target temperature deviation that can be eliminated using bypass is illustrated in figure-4.6, now for an expected inlet disturbance the target temperature deviation is calculated using the disturbance model and the required nominal bypass fraction is interpolated. Figure-4.7 illustrate that the cost of installing a bypass is more economical than installing a utility heat exchanger to control stream H1 target temperature along the curve of the disturbance that installing a bypass can eliminate.

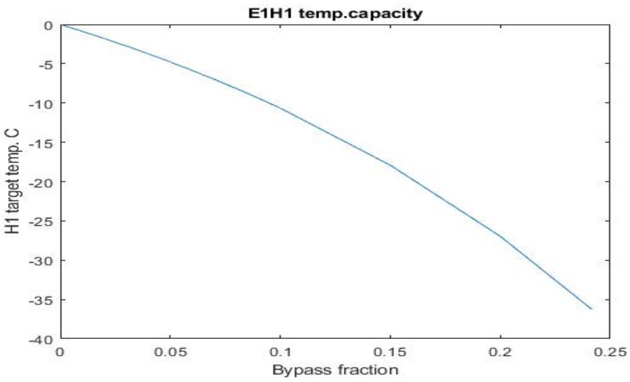

Fig 8 Nominal bypass fraction temperature deviation capacity

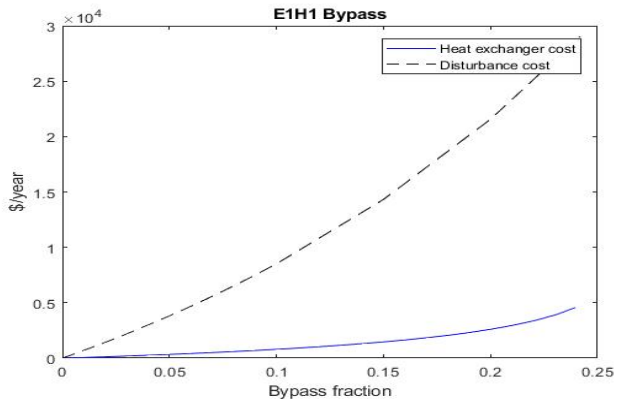

Fig 9 Tradeoff between the cost of the disturbance and the cost of installing bypass

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B. *Target temperature of stream H2 using heat exchanger E3 cold side.*

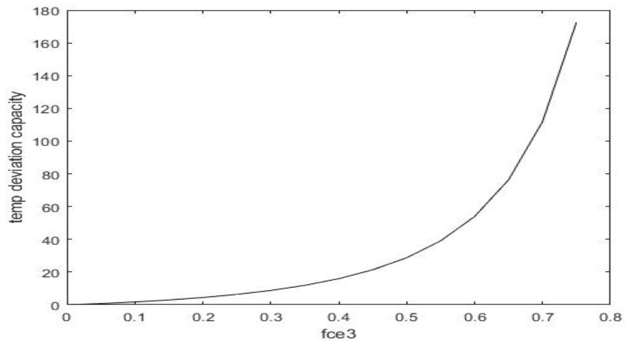

Fig 10 Nominal bypass fraction temperature deviation capacity

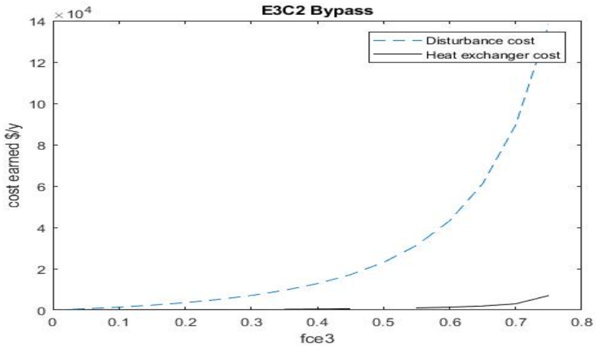

Fig 11 Tradeoff between the cost of the disturbance and the cost of installing bypass

C. *Target temperature of stream C1 using heat exchanger E2 hot side.*

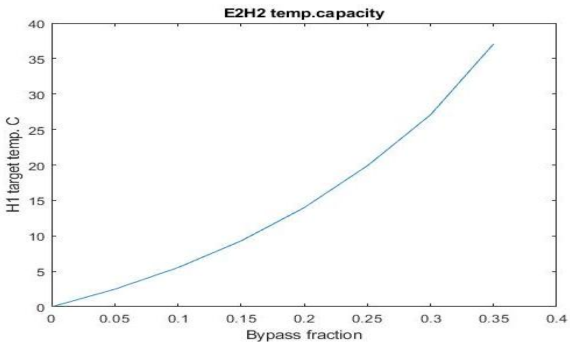

Fig 12 Nominal bypass fraction temperature deviation capacity

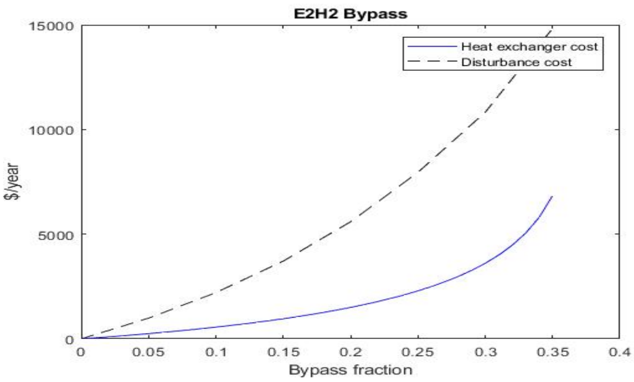

Fig 13 Tradeoff between the cost of the disturbance and the cost of installing bypass

V. CONCLUSION

Heat exchanger networks HENs are complicated systems with the possibility of producing unwanted disturbances that can cause serious economic consequences, unsatisfying operation results or even destroy the system feasibility. In this work a linear model was constructed to evaluate the disturbance in streams target temperatures. Each exchanger in the network is represented by a set of algebraic equation with neglect high order differentiation terms. The model can be used to estimate the maximum deviation of system outputs. The determination of heat exchanger network target temperature can be carried out in different ways. Several equations can be applied to find outlet temperatures of a network. It is easy to use computationally efficient and particularly helpful in analyzing integrated process systems where disturbance propagation is always a major concern. The efficacy of using the model demonstrated by solving practical industrial problems demonstrate the applicability of the model in process analysis and improvement.

The work presented in this thesis can be applied to any HEN to increase its ability to reduce and eliminate the disturbance with cost consideration.

Ns-RGA showed very reliable method for the pairing the controlled with manipulated variables to provide a good control scheme.

Using the condition number proved a better solution to measure the controllability and provide a comparison between different control schemes for the same HEN.

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