STUDY OF THE HEAT EXCHANGER NETWORK FLEXIBILITY

S. A. ABDEL–MONEIM, G. R. ASSASSA, S. A. AFIFY* and M. E. AWAD**

Mech. Eng. Dept., Faculty of Eng. (Shoubra),, 108 Shoubra St., Cairo, Egypt
* *Post graduate Student*
** *Faculty of Petroleum and Mining Eng. Suez Canal Univ.*

ABSTRACT
Heat exchanger network (H.E.N) is a key aspect of chemical process design and about 30% energy saving coupled with capital saving can be realized by improving the H.E.N design. The objectives of this work are: i) to study the flexibility of H.E.Ns under the simultaneous variations of temperature, heat capacity flow rates and the product of the overall heat transfer coefficient and the area of the heat exchanger. ii) to highlight the dangers and the opportunities for developing a practically applicable technique. Also, a modified method for the flexibility study of H.E.Ns was developed from the combination of two systematic computational methods (sensitivity analysis and heat load shift method). In this method the passive response of the network to the deviations in feed temperature, flow rate, heat transfer coefficient was evaluated by using the sensitivity analysis method while the possible design changes, which are required to eliminate the unwanted passive responses, were determined by using the heat load shift method.

1. INTRODUCTION

For a certain number of hot streams to be cooled and a nother number of cold streams to be heated from specified supply temperatures to specified target temperatures, the design of a network of heat exchangers, heaters and coolers accomplishing this task at the least cost is the standard heat exchanger network problem as stated by Masso and Rudd [1] in 1969.

This problem attractes the interest of investigators for two reasons. The first is that, the heat exchanger network is an important industrial energy management tool for which only empirical design methods are existed. The second is that, this abstraction of the design problem is the most clearly defined problem compared to all available process synthesis problems. For these reasons the H.E.N problem becomes the playground of the design theorists and contained the promise of new methods useful to the design practitioners.

Generally, Processes have to be flexible because of turndown requirements, seasonal variations, catalyst deactivation, changes in feed stock, and product specifications, etc. Good flexibility requires a significant cost implication. Therefore, rising energy costs have created an incentive for developing efficient energy systems. As a result, there has been a trend towards using more highly integrated processes. This in turn has essential fostered concern that the operability and flexibility will suffer.

The flexibility study of the H.E.N shows the engineers which exchanger in this process governs flexibility and what are the limits and sensitivities.
They allow engineers to depart from specified flexibility levels and to thoroughly address the following two issues:

1. Which design will give flexibility most cheaply?
2. How much flexibility is cost effective?

The latter question is quite separate and important. Design can be too flexible from overall cost points of view by adjusted trade off in three dimensions: flexibility capital and energy as shown in Fig.(1).

The good operability of chemical processes is essential, plants, have to work with a range of throughputs, a range of product specifications, seasonal variation, and with the problems of catalyst deactivation and fouling, start up and shutdown are vital, the cost penalties of poor operability may be significant.

The traditional design approach of a process is to develop a flow sheet for the base case, optimize it, add contingency for flexibility and finally develop the control strategy. Contingency often costs high, so its addition to an optimized base case invalidates the optimization; however, the prevailing attitude tends to be that, while the add-on cost of operability is high, it is also inevitable.

Generally, ideal optimization of a process should involve the following three aspects:

1. Capital costs.
2. Operating costs (mainly energy consumption).
3. Operability costs (throughput, product purity, etc).

These aspects need to be quantified and compared; also the optimization will be achieved by concerning the flexibility of heat exchanger network.

The major component affecting the overall performance of processing systems is the heat recovery network .The task of the heat recovery network is the exchange of the available heat of all process stream in order to reduce the consumption of heating and cooling utilities. Since the cost of utilities is usually the dominant item, there is a great incentive to design heat recovery networks that will be flexible.

On view of the previous introduction, the main goals of this study are to highlight the methods of the flexibility of H.E.N and to analyze the common methods introducing the advantage and drawbacks of each method in addition to a detailed comparison between them.

Besides, a combination between two methods was made to deduce modified method that collecting all advantages and avoiding disadvantages of the two methods.

2. THE PRESENT MODIFIED METHOD

In the present paper, a modified method that combines the advantages and avoids the drawbacks of the main flexibility study methods was concluded by a combination between the presented methods heat load shift and sensitivity analysis.

The modified method enables the engineer to:

1. Evaluate the passive response of the network to the deviations in the feed temperatures, flow rates, heat transfer coefficient by using sensitivity technique [33].
2. Evaluate all possible design changes to eliminate unwanted passive responses by using the heat load shift technique [71].

Moreover, a computer program is presented in appendix to simplify the solution by this method.

2.1. Theory of The Procedure

2.1.1. Passive response

The present procedure was applied to the single heat exchanger shown in Fig.(2) as an illustrative example for which the heat balance equations are:

$Q = C_H (T_1 - T_2)$, $Q = C_c (T_4 - T_3)$ and the design equation is: $Q = UA (T_{LM})$. These equations can be transformed into:

$$(1-RB)\ T_2 + (B-1)\ R\ T_3 + (R-1)\ T_1 = 0 \quad (1)$$

$$R\ (1-RB)T_4 + (B-1)RT_1 + (R-1)BRT_3 = 0 \quad (2)$$

Where,

$$R = C_c/C_h$$

$$B = e^{[\,(UA/Cc)\,(R-1)]}$$

The governing equations, Eq.(1) and (2) are linear in the temperatures but they are non-linear in the heat capacity flow rates and also non-linear in the (UA) product. Therefore, if C_h, C_c and any two out of the four temperatures T_1, T_2, T_3, T_4 are assumed to be known , it is always possible to solve the system of equations (1) and (2) without iteration to find the missing two temperatures .

The response of a simple network is determined in two stages:

1. Determination of what calculations are needed and their order (i.e. a route through the network is identified.)
2. Solution of the response equations
3. Comparing the old value with the new one to obtain the temperature change.

2.1.2. Design change

Restoration of target temperatures requires the shifting of heat loads about the network. As first noted this can be achieved through the installation of additional area; the use of exchanger by-pass; or the direct use of utility.Whilst target temperatures are initially set at required values, variations within set upper and lower temperature bounds can be considered acceptable. So, the first step in analysis the response of a network to imposed disturbances is obviously a comparison between the resultant target temperatures and the specified bounds. The result is a picture of heat supply and demand across the network.

If a target temperature falls outside of the bounds, the load to restore it to the nearest bound can be considered to be the required load shift.

It will be given by either:

$$Q^{\wedge}_{R} = Q^{\wedge +} = C\ (T - T_{max}) \qquad T > T_{max} \quad (3)$$

or:

$$Q^{\wedge}_{R} = Q^{\wedge -} = C\ (T - T_{min}) \qquad T < T_{min} \quad (4)$$

An examination of the required shift gives an immediate indication of what form of remedial action is required. If the required shift on a cold stream is positive ($T > T_{max}$; $Q^{\wedge}_{R} = Q^{\wedge +}$) too much heat has been added to the stream. The remedial action must be the provision of a by-pass around one of the exchangers on the stream .If the required shift is negative ($T < T_{min}$; $Q^{\wedge}_{R} = Q^{\wedge -}$) insufficient heat has been provided to the stream and additional area is needed on one of the exchangers. Similarly, if the required shift on a hot stream is positive ($T > T_{max}$; $Q^{\wedge}_{R} = Q^{\wedge +}$) in - sufficient heat has been removed and additional area is necessary . A negative value indicates the removal of too much heat and the need for a by-pass. These observations are summarized in the following Table (1).

Table. (1): Heat load shifts and the require action.

Stream	Required load shift	Action
Hot stream	+ ve - ve	More area By pass
Cold stream	+ ve - ve	By pass More area

If a target temperature is well within its required bound, it has a required shift of zero. However, with such a stream there may still be scope for shifting heat down the paths by going to one of the bounds. Such heat load shifts can also generally be undertaken in either direction. The available shifts are given by:

$$Q^{+} = C\ (T - T_{min}) \tag{5}$$

or

$$Q^{-} = C\ (T - T_{max}) \tag{6}$$

Finally, it is recognized that streams having a required heat shift also have an available shift. This shift is in the same direction as the required shift and is that load that is necessary to take the stream to the furthest bound.

2.1.2.1 Additional area needs

A change in effectiveness can be converted into changes in area once the type of exchanger is known. for instance for a pure counter current arrangement, thermal effectiveness and number of transfer units are related according to

$$\varepsilon = (1 - e^{-NTU(1-R)})\ /\ (1 - R\ e^{-NTU(1-R)}) \tag{7}$$

From this expression:

$$NTU = \ln\{(1 - R\varepsilon)\ /\ (1 - \varepsilon)\} / (1 - R) \tag{8}$$

If $NTU^{(0)}$ and $NTU^{(N)}$ be the initial and the new exchanger number of transfer units respectively, then the NTU change is given by

$$NT\hat{}U = \ln\{(1 - R\varepsilon^{(N)})(1 - \varepsilon^{(0)}) / (1 - R\varepsilon^{(0)})(1 - \varepsilon^{(N)})\} / (1 - R) \tag{9}$$

This equation gives the required NTU increase in the exchanger, which must undergo in order to meet a specified target temperature. The additional area can be calculated from

$$U\ \hat{}A = NTU\ R\ min \tag{10}$$

2.2 Flow rate calculation

Since the effectiveness of an exchanger is a function of C ratio, a change to the mass flow rate of either of the streams about a single exchanger will result in a change to the thermal effectiveness of the unit. By-pass can therefore be used to achieve a desired temperature correction. Consider manipulation of the stream exhibiting the lowest C. The fraction of the flow of manipulated stream actually passing through the exchanger will be represented by f. For a by-pass to be applicable the exchanger must be larger than actually needed for one of the operating cases. Assume that this is the base case and under this situation the bypass operate partially open and $f^{(0)}$ is the fraction of the flow passing through the exchanger. If temperature T_2 in Fig.(3) needs to be reduced the bypass valve must be closed. Conversely, when T_2 is to be increased the bypass value opens. Assume the new flow fraction through the exchanger becomes $f^{(N)}$. Denoting $T_2^{(o)}$ as the initial condition of T'_2, the following expression can be written:

$$\mathbf{T_2^{(o)} = T_1 - \Delta\, \varepsilon^{(o)}} \qquad (11)$$

A heat balance about mixing point gives

$$\mathbf{T_2^{(o)} = (1-f^{(o)})\, T_1 + f\, T'_2{}^{(o)}} \qquad (12)$$

Combining the two equations yields

$$\mathbf{T_2^{(o)} = T_1 - f^{(o)}\ \Delta\, \varepsilon^{(o)}} \qquad (13)$$

When by pass valve operates then T'_2 becomes $T'_2{}^{(N)}$ and is given by

$$\mathbf{T'_2{}^{(N)} = T_1 - \Delta\, \varepsilon^{(N)}} \qquad (14)$$

Again, heat balance about mixing point gives

$$\mathbf{T_2^{(N)} = (1- f^{(N)})T_1 + f^{(N)}\, T'_2{}^{(N)}} \qquad (15)$$

Combination of equations (14) and (15) gives

$$\mathbf{T_2^{(N)} = T_1 - f^{(N)}\, \Delta\, \varepsilon^{(N)}} \qquad (16)$$

The total change in outlet temperature T_2 can be obtained by combining equations (13) , (16)

$$\mathbf{\hat{T}_2 = - \Delta\, (f^{(N)}\, \varepsilon^{(N)} - f^{(o)}\ \ \varepsilon^{(o)})} \qquad (17)$$

A similar analysis performed for temperature t_2 gives

$$\mathbf{\hat{t}_2 = R\, \Delta\, (f^{(N)}\, \varepsilon^{(N)} - f^{(o)}\ \ \varepsilon^{(o)})} \qquad (18)$$

In the case where the by-pass valve operates between an initial condition of fully closed and a final condition of partially open , then $f^{(o)} = 1$ and $f^{(N)} = f$. Equation (17) reduced to

$$\mathbf{\hat{T}_2 = - \Delta\, (f\, \varepsilon^{(N)} - \varepsilon^{(o)})} \qquad (19)$$

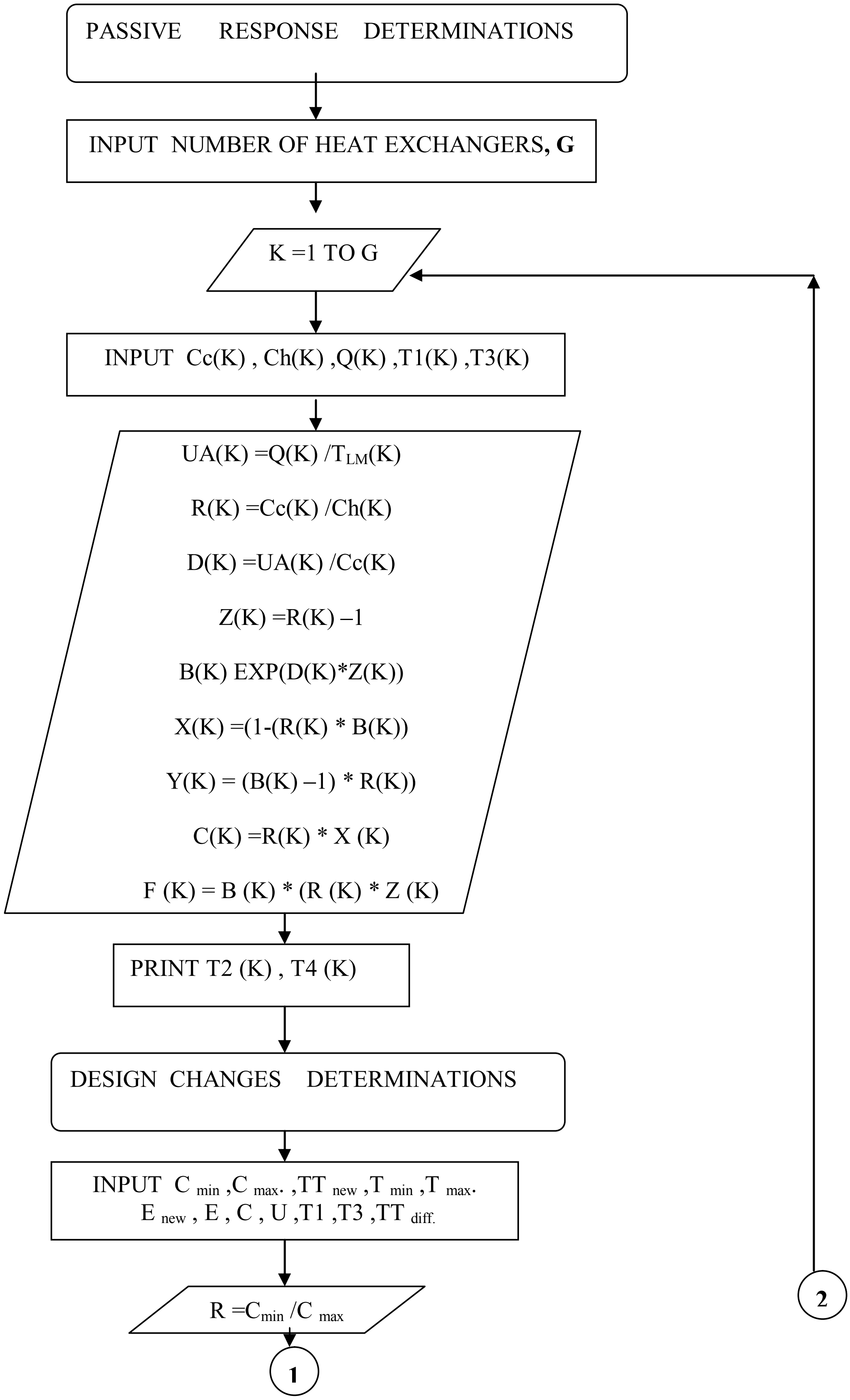
Similarly it can be shown that

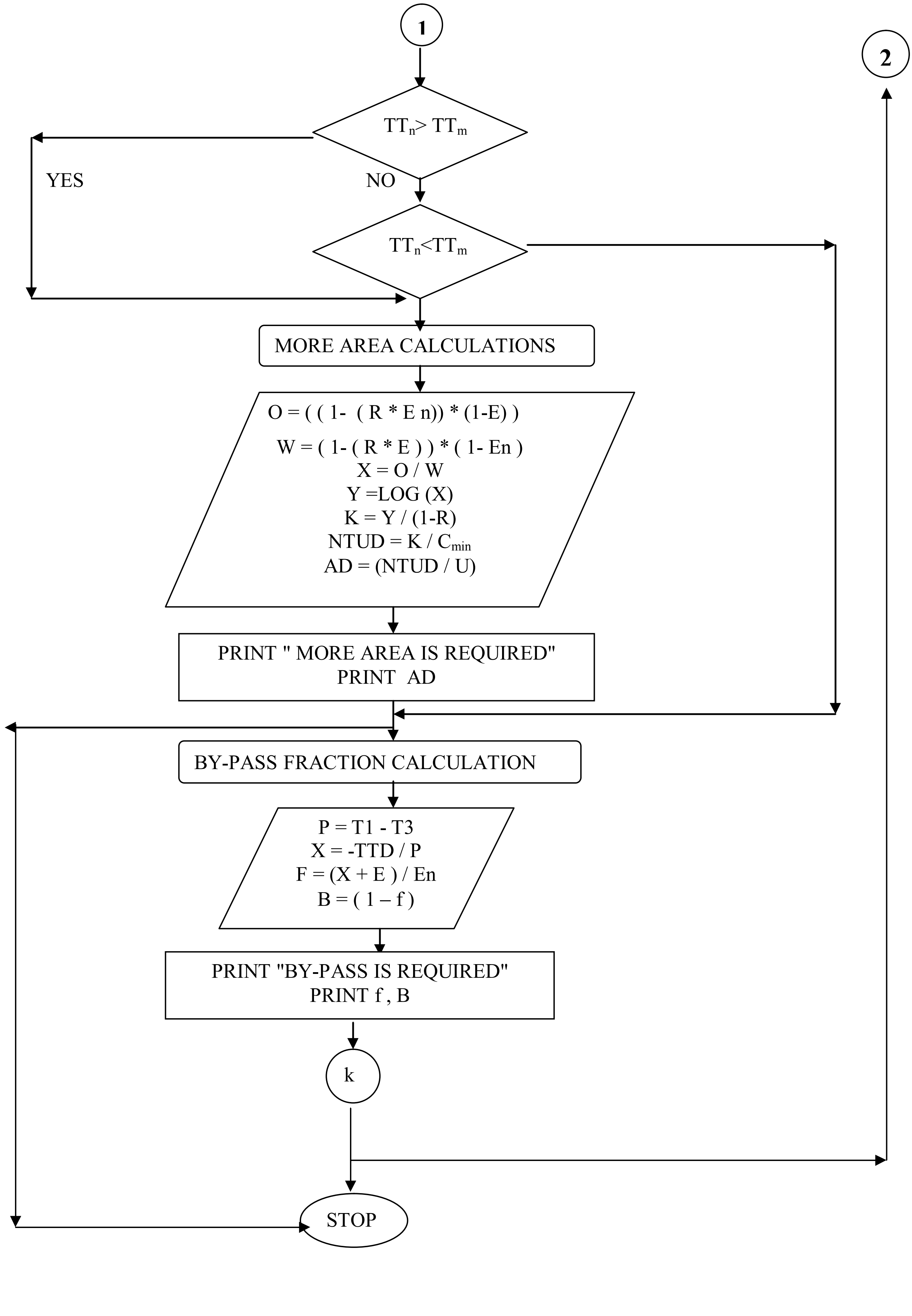
$$\mathbf{\hat{t}_2 = R\, \Delta\, (f\, \varepsilon^{(N)} - \varepsilon^{(o)})} \qquad (20)$$

Then the flow rate fraction is:

$$\mathbf{f = [(\hat{t}2 / R\, \Delta) + \varepsilon^{(o)}\,] / \varepsilon^{(N)}} \qquad (21)$$

2.3. Program Flowchart




1
2
TTn> TTm
YES
NO
TTn<TTm
MORE AREA CALCULATIONS
O = ((1- (R * E n)) * (1-E))
W = (1- (R * E)) * (1- En)
X = O / W
Y =LOG (X)
K = Y / (1-R)
NTUD = K / Cmin
AD = (NTUD / U)
PRINT " MORE AREA IS REQUIRED"
PRINT AD
BY-PASS FRACTION CALCULATION
P = T1 - T3
X = -TTD / P
F = (X + E) / En
B = (1 – f)
PRINT "BY-PASS IS REQUIRED"
PRINT f , B
k
STOP

3. CASE STUDY (1)

The downstream path procedure for H.E.N flexibility study represents a stepping stone in process optimization. So, it will be appreciated to concentrate on the downstream path with practical case study. Also in this section it will be appreciated to introduce two case studies as a practical application on the presented modified method by using the developed computer program.

Figure (4) shows simplified flow sheet of vacuum distillation unit. The revenant heat exchanger network is shown in Fig. (5) using the grid representation. Data describing the current operation of the plant are given in Table (2).

The plant is to be retrofitted to operate on a different duty for a single campaign once a year. The length of the campaign is approximately two months. A new feedstock is to be used. Flow-rates within the plant need to be increased and some temperatures are changed. As mentioned in the introduction, Case B is described as a set of deviations from case A. the data describing case B are given in Table (2b). Case B operation has another complication. The temperature of stream No. 1 is increased significantly (see Table (2b) and this is known to result in exchanger fouling at temperatures in excess of 280°C thus, exchanger No. 1 in Fig.(5) will operate clean during case A operation but will be subjected to fouling, to a significant extent, during case B operation.

Table (2): Stream data describing current plant operation (CASE A) and the new alternative duty (CASE B).

(a)	Case A	(10 months /	Year)	
Stream No.	**Ts**	**TT**	**C (kW/°C)**	**U(kW/m² °C)**
1	285	218	81.49	0.35
	218	150	69.71	0.28
	150	120	66.97	0.24
2	272	151	49.17	0.50
	151	75	44.41	0.41
	75	40	43.29	0.40
3	55	115	55.87	0.2
4	40	102	76.45	0.
	102	175	81.51	0.41
	175	236	89.51	0.47
	236	315	97.1	0.53
(b)	**Case B**	**(2 months /**	**Year)**	
Stream No.	**Ts**	**TT**	**C (kW/°C)**	**U(kW/m2 °C)**
1	+40	-	+30%	-
2	-20	-	+10%	-
3	-	-	+20%	-
4	-	-	+20%	-

The design objective for the retrofit is to find the flexible H.E.N which will enable in future both case A and case B operations. All specified flows and temperatures must be maintained.

The passive response results that introduced by simulation are shown above in Fig.(6). The target temperature TT_1, TT_2 and TT_4 can be maintained by utility exchangers. But the target temperature TT3 is reduced by (7.4 °C) and that can be maintained by installing heat on stream No. (3) to increase TT3 to 115°C.

3.1. Passive Response

Applying The Modified Method Using A Computer Program.The new value of the target temperature TT_3 after the retrofitting of the H.E.N as mentioned in Table (2) can be calculated by applying the developed software of the modified method, the resultant temperature of TT_3 is 107.6°C. So it is necessary now to find the order of design change to keep the value of TT_3 at the initial value of 115°C.

3.1. Design Change

In order to build the flexibility into the present H.E.N ,it is necessary to carry out the suitable change in the initial design. By applying the software program of the modified method, the resultant design change is found to be over-sizing the heat exchanger No.3 or to install a new heater on stream No.3 with total are of 34 m^2 as shown in Fig.(7). So, the design can be changed by installing a small heater equivalent to the required area or over-sizing exchanger E3 on stream No. 3 to increase the temperature from 107.6 °C to 115 °C ,also to avoid any disturbance in the future as shown in the grid Fig.(7). The developed solution matched with that found by Linnhoff and Kotjabasakis [9].

4. CASE STUDY (2)

An aromatics plant having the heat recovery network shown in Fig.(8) (multi-stream heat exchanger network). The plant was retrofitted for the following changes:

1. 20% increase in the flow rate of stream H4
2. 10 degree fall in inlet temperature of stream H3
3. 20 degree rise in inlet temperature of stream C1

The critical temperatures are: the outlet temperature of exchanger E4 (stream C 1), inlet temperature to the first reactor (stream C 2), inlet temperature to the second reactor (stream C 3) and the feed to the distillation column (stream C 5). The network is worked in the base case under the following data:

Table (3): Base case data

Strem	C (kW/°C)	Exchanger	ε
H1	100	E1	0.3115
H2	160	E2	0.807
H3	65	E3	0.3
H4	400	E4	0.42
C1	120	E5	0.4700
C2	70	E6	0.7445
C3	350	E7	0.8097
C4	60	E8	0.82425
C5	200		

The passive response values of this network after retrofitting caused by the disturbances in target temperatures of streams H1,H3,H4 and C5 can be manipulated by using utilities such as coolers and heaters. For streams no. H2, C1, C2 and C3 the computer program can be applied to find the appropriate corrective actions.

4.1. Passive Response

The new value of the target temperature TT_6, TT_{17}, TT_{21}, TT_{23} and TT_{25} after retrofitting of the H.E.N as mentioned can be calculated by applying the developed software of the modified method, the resultant temperature values as follows:

T	^oC
TT_{21}	174.9
TT_{23}	146.6
TT_6	159.6
TT_{12}	199.5
TT_{25}	167.77

4.2. Design Change

The flexibility into the present H.E.N can be built by applying the computer code to find the recommended design change. The observed results as follows:

St.	ACTION	Area (m^2)	f	B
H2	By-pass is required around E3	-	0.348	0.652
C1	By-pass around E4	-	0.456	0.543
C2	By-pass around E1	-	0.431	0.568
C3	More area is required	65.52	-	-
C4	More area is required	6.74	-	-

5. CONCLUSIONS

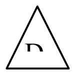
1. A consideration of the function and behavior of heat exchanger networks (H.E.N) leads to understanding procedures that can be effectively employed for the solution of operability problems.
2. Solving an operability problem means that, critical exchangers within a network must be found and then the appropriate corrective actions (additional area or by – passes) should be carried out to ensure that all network temperature are within acceptable bounds.
3. The main steps that lead to the identification of the most suitable strategy to achieve the task can be summarized as follows:
   a. Specify stream temperature bounds.
   b. Determine the response of the network to imposed disturbances.
   c. Devise the strategy for the shifting of heat within the network.
   d. Determine the order in which the modifications should be undertaken.
   e. Apply the corrective equations to calculate the required additional area or the by-pass for the various involved exchangers.
4. Good integration lead to lower capital cost, and at the same time, betters operability.
5. Regarding to the present modified method, the heat load shift philosophy indicates what type of corrective actions needed (additional area or exchanger by-pass) and shows the designer which streams can be manipulated in order to satisfy the flexibility requirements.
6. The rule of design changes is based upon the concept:

"First the number and then the size of the change should be kept to a minimum".

7. With flexibility considerations, the design may seem to be expensive for the short-term operations but it will be the cheapest design in the long-term operations and will give trade of between the capital cost and energy.
8. The effectiveness of the presented modified method computer code was demonstrated on two case studies to highlight the proposed design changes in order to adjust the network target temperatures.

NOMENCLATURE

Unless otherwise stated, the symbols used in the thesis have the following meanings and SI system of units is used:

Symbols		**Subscripts**	
A	heat exchanger area	**B**	base case
R	heat capacity flow rate ratio	**K**	refers to K^{th} equation
C	heat capacity flow rate	**LM**	logarithmic mean value.
Cc	heat capacity flow rate for cold stream	**O**	out put
C_h	heat capacity flow rate for hot stream	**max**	maximum.
C_1	heat capacity flow rate for stream No. 1	**min**	minimum
f	mass flow rate fraction		
h	heat transfer coefficient	**Superscripts**	
M	mass flow rate/ No. of heat exchangers	**N**	new conditions
NTU	number of transfer units	**O**	initial conditions
N	number of streams	^	Change
Q	exchanger heat load	**1,2,r**	iteration numbers
QR	required heat load shift		
S	matrix symbol	**Greek letters**	
T	hot stream temperature	**δ**	temperature disturbance
t	cold stream temperature	**Δ**	Maximum temp. difference
Ts	supply temperature	**ε**	thermal effectiveness
TT	target temperature	α_1, α_2	Defined in equations No. 5-6,5-7
U	over all heat transfer coefficient	**Ø**	vector deviations in network temperatures
		Abbreviations	
			Disturbed
			Controlled

REFERENCES

1. Masso A.H. and Rudd D.F., " Synthesis of the Heat Exchanger Network" AIchE. J Vol.15 No.10, 1969.
2. Marselle et.al "Design of resilient Heat Exchanger Network" Eng. Sci, Vol. 37 No. 2,PP. 259, 1982.
3. Saboo, A.K. and Morar: M., "design of resilient processing plant", Chem. Eng. Sci (39) 3:579, 1984.
4. Sawny, R.E. and Grossman, I.E., "Operability study of Flexible Heat Exchanger", AIchE. J, 31(4): 621, 1985.
5. Kotjabasakis E. and Linnhoff B. " sensitivity Tables for the Design of Flexible Processes. " Chem. Eng. Res. Div., Vol. 64, PP.197-211, 1985.
6. Floudas, C. A. and Grossmann, I.E., "Synthesis of flexible heat exchanger networks for multi period operation comp". Chem .Eng, Vol. 10 No.2 , PP.152-168, 1986.

7. Linnhoff, B. and Kotjabasakis, E.," Downstream paths for operable process design", Chem Eng Prog, Vol. May ,1986.
8. Pistikopoulos and Grossmann, I.E., "Synthesis of flexible heat exchanger networks ",comp. Chem. Eng, 1988.
9. Colberg and Morari, " Analysis and Synthesis of Resilient Heat Exchanger Network" Chem., Eng. Sci.Vol. 14 ,1988
10. Cerda J. et.al "The synthesis of flexible heat exchanger network with MILP"., Chem. Eng. Sci. 39,1989
11. Rantam R. and Patwardhan V. S. "sensitivity analysis for heat exchanger networks" chem. Eng. Sci Vol. 46,No.2,PP. 451-458 ,1990.
12. Papalexandri, K. P. and Katerina " design of operable H.E.N " Ind. Chem. Eng. Res Vol.8.No. 36, 1993.
13. Picon M. ,Nunez and Polly G. T. "determination of the steady state response of heat exchanger network without simulation" trans. I chem. (AI)Vol.73,PP. 48 – 58 ,1995)
14. Picon M. Nuenez and Polley G. T. "applying basic under standing of heat exchanger network behavior to the problem of plant flexibility" trans. I. Chem. Vol.73,PP.941-952,1995.
15. Zhang J; Zhu XX "simultaneous optimization approach for heat exchanger network retrofit with process changes" Ind. Eng. Chem. Res. Vol.39 ,2000.
16. Book reference "User guide on process integrate on for the efficient use of energy " the institute of chem. Eng. 1986
17. Ennpi Co. Design Dept. "Lecture for heat exchanger network design",1993.
18. Harary F., "Graph theory, "Addison – Wesley, reading, mass ,1972.
19. Geoffrion A.M. "Generalized Benders Decomposition". J.Opt. theory APPL. Vol.10, PP.237 ,1972.
20. Linnhoff, B., "Thermodynamic Analysis in the Design of Process Network" Ph.D. thesis, University of Leeds, England ,1979.
21. Sood K. and Reklaities G.V. and Woods, J. M., "Solution of mater balances for flow sheets modeled with elementary modules unconstrained case", AIchEJ, Vol. 25 No.2 PP.209-219, 1979.
22. Linnhoff, B., and Aurner J. " Design of operable Heat Exchanger Network" Chem. Eng., Vol. Nov.2 ,PP.56 ,1981.
23. Linnhoff and E. Hindmarsh, "the pinch designs method for heat exchanger network", Chem. Eng. Sci Vol.38, PP.745 ,1983.
24. Cerda J., Westeberg A.W., Mason D. and Linnhoff, B." minimum utility usage in H.E.N synthesis", Chem. Eng. Sci, Vol.38, PP.373,1983.
25. Grossman I.E, Halemane K.P., and Swaney R.E.," Design of Flexible Heat Exchanger" Comp. And Chem. Eng., Vol.7 No.4, PP. 439 ,1983.
26. Linnhoff, B., and. Vredeveled, D.R "Retrofitting of Heat Exchanger Network"Chem. Eng. prog. p.33 ,July, 1984.
27. Asbjornsen, O.A. and Haug, M., paper No. 16, Process systems Engineering Conference, PSE85 I Chem E. Symposium Series No. 92, 197, , 1985.
28. Fryer, P.J., Paterson, W.R. and Slater, N. K. E. "Design of Flexible H.E.N (I) "(university of Cambridge) , 1985.
29. Fryer P.J., Paterson W.R. and Slater N.K. E. "Design of Flexible H.E.N (II) " University of Cambridge, 1985.
30. Linnhoff March Consultants Ltd "Cost reduction on an Oil refinery efficiency" Shell (UK) Ltd.., published by the Energy Efficiency Office, U.K. Dept. Of energy (1986).
31. Kotjabasakis, E. and Linnhoff, B., "Sensitivity Tables for the design of flexible processes (2) A case study". IchemE Symp. Ser No. 109, 1988.
32. Saboo A. K., Morari, M. and Wood Cock O, "design of resilient processing plants" VΠ. chem. Eng. Sci Vol. 40 ,No.8.PP 1553 – 1565, 1995.

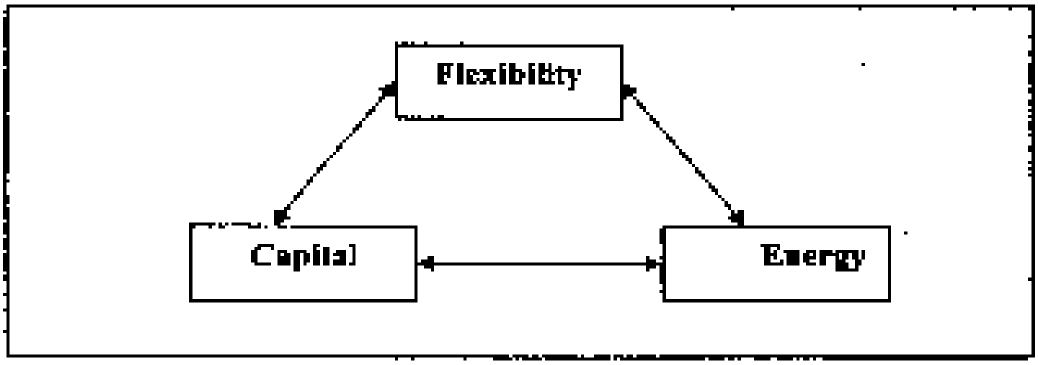


Fig. (1) : Three – ways trade off between Energy, capital and flexibility [33].

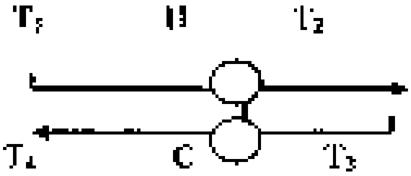


Fig.(2): Single heat Exchanger

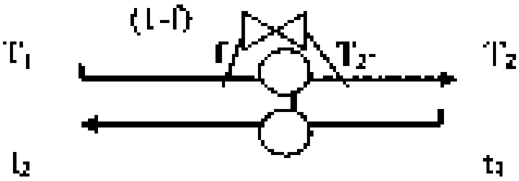


Fig.(3): Heat Exchanger fitted with by-pass .

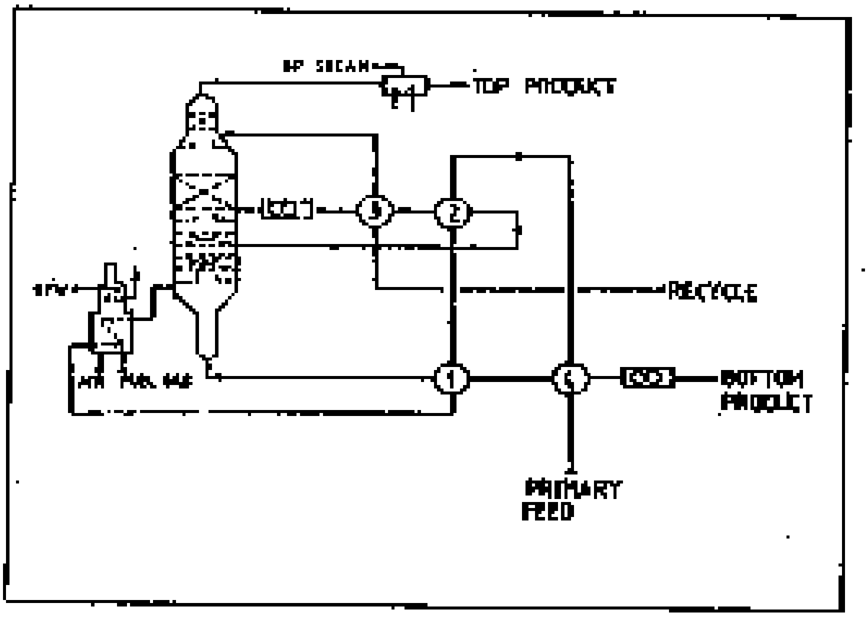


Fig.(4): Simplified flow sheet for a vacuum distillation unit .

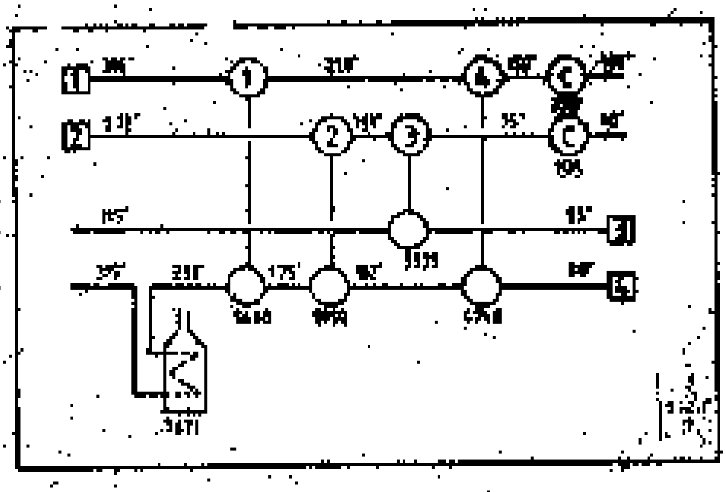


Fig.(5) The existing network before retrofit (case A)

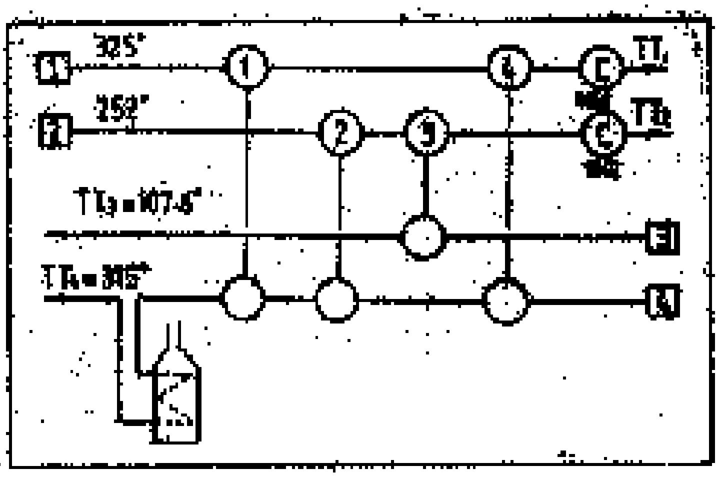


Fig.(6) Passive response

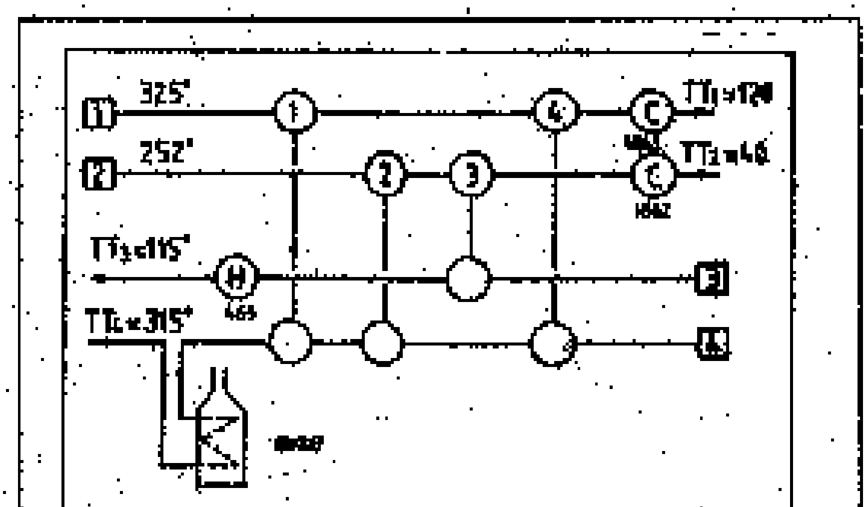


Fig. (7) : Install a new Heater or over-sizing E3

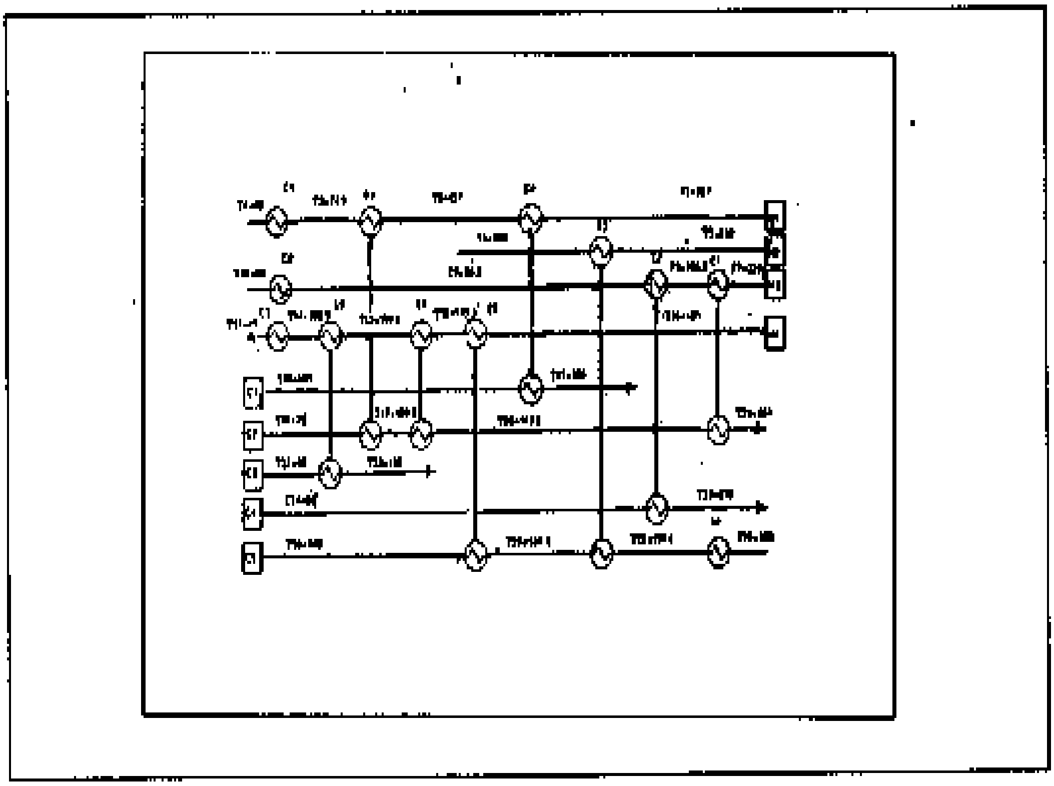


Fig. (8) : Multi-stream H.E.N grid representation