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P3B-10: DETERMINATION OF OPTIMAL MASS SEPARATING AGENT FOR THE REMOVAL OF POLLUTANT FROM INDUSTRIAL WASTES USING MASS EXCHANGER NETWORKS SYNTHESIS

G. B. Adebayo, O. S. Azeez*, A. S. Abdulkareem
Department of Chemical Engineering, School of Infrastructure, Process Engineering and Technology, Federal Universityof Technology, P.M.B 65, Main Campus, Gidan-Kwano
Minna, Niger State, Nigeria
*Corresponding author email: tosin.azeez@futminna.edu.ng

Abstract

Wastes and Emissions from chemical plants have over the years contributed to the environmental pollutions. End-of-pipe treatments alone cannot effectively mitigate the effects of chemical processing facilities because of their complexity, it is important for pollution prevention to be considered from the beginning of chemical process synthesis steps. Therefore, this study focuses on the determination of optimal mass separating agent (MSA) for the removal of a pollutant from industrial wastes using mass exchanger networks synthesis (MENS). Pinch y-y tool was used to determine the most suitable external MSA for MENS problem with multiple MSAs (S_3, S_4, S_5 and S_6) and to target for capital cost and total annual cost (TAC) for the network before actual design. From the result of the designs, MSA (S_3) shows to be the most suitable and economical, followed by S_6, S_4 and S_5 respectively. It can be inferred from the results that these methods can be used to screen and select MENS problems with multiple MSAs options quickly and effectively. This also reduces the design cost as well as minimizing the emission of pollutants into the environment.*

Keywords: Capital cost targets; Mass exchanger networks; Mass separating agent; Pinch technology, Pollution

1.0 INTRODUCTION

Research in process synthesis over the years has been driven by the desire to enhance process performance and profitability while reducing the environmental impact. The effort to improve yield and profitability will have to be simultaneously achieved along with reductions in energy consumption, impressive process flexibility, process and environmental safety, product quality enhancement, waste recycling and reuse and pollution prevention (Keller and Bryan, 2000).Industrial wastewater can be used for irrigation to increases agricultural production, thus contributing to food safety. The nutrients that are possibly contained in waste water can thus allow for savings on purchase of fertiliser. Nevertheless, the risks of industrial waste water re use in agriculture and other activities can be extensive in terms of public health problem if necessary, steps are not taken before and after re use. The prevention of pollution can therefore, be a great benefit associated with industrial waste reuse but necessary steps will have to be taken to ensure safety of public health.

Chemical processing facilities vary from simple connections of units to complex networks of units of equipment and streams. The environmental issues emanating from such complex system cannot be effectively mitigated by just end-of-pipe treatments. Pollution prevention through system integration should be taken into account from the beginning of process synthesis steps. The environmental performance and cost effectiveness of a process will depend on the performance of the various unit operations and process integration. Achieving global insights into the nature of heat and mass flow of processing facilities enable pollution reduction at the source as well as cost effectiveness of the process (Linnhoff and Ahmad, 1989; Agrawal and Sikdar, 2012; Azeez, 2011).

Chemical process synthesis involves the systematic development of process flow sheets that can effectively transform available raw materials into desired products that will meet specified performance criteria of minimum cost of productions, energy efficiency, maximum raw material recovery, minimum waste production and excellent operability (Smith, 2016). It answers the question of which unit operation should be used and the way it should be approached in order to provide the best possible solution to a synthesis problem. One of the design approaches that have been adopted in recent times is the integration of the systems that make up the processes. Process integration is a tool that have been used to accomplish some of the goals in process optimization. Some of the task that have been accomplish using the process integration include improved sustainability by reducing the process waste discharge, effective use of raw materials, reduction in the purchase of external energy utilities and mass separating agents and minimising the generation of emissions and wastes (Kaggerud et al, 2006). It is a system-oriented, thermodynamics-based, integrated approach to the analysis, synthesis and retrofit of process plants. (El-Halwagi, 1997; Linnhoff et al., 1982; Linnhoff and Ahmad, 1989).

There are two main approaches to process integration; the pinch technology approach and the mathematical optimization approach. In pinch technology, the designer uses physical and thermodynamic concepts to set up and optimise the task to be synthesised (Linnhoff and Vredeveld, 1984).Mathematical programming approach involves setting up a mathematical framework which is supposed to embed all possible alternative structures using different types of mathematical constraints. The framework is subsequently optimised subject to the constraints in order to obtain the optimum structure (Azeez, 2011; Isafiade, 2008).

In the application of process integration, several optimisation techniques have been developed in order to reduce the usage of material and energy resources as well as discharge of wastes (Wang and Smith, 1994; Hallale and Fraser, 2000a&b; Tjan et al., 2010; Ponce-Ortega et al., 2010;Papalexandri et al.,1994; Azeez, 2011 ; Foo et al., 2005).

Heat Exchanger Network Synthesis (HENS) had been given more attention over MENS; this was due to the rising cost of energy in the seventies (Gundersen and Naess, 1988; Linnhoffand Ahmad, 1989; Yee and Grossmann., 1990). Also, concern has been raised by various regulatory bodies on the effect of process industries emissions into the environment. This has necessitated the development of integration methods for mass exchange network synthesis (El-Halwagi, 1997; Hallale and Fraser, 2000a&b).Mass exchanger networks has now become parts of the separation networks of the chemical plants, MENS seeks to clean the emanating process streams before they are released to the environment. MENS reduces the amount of external MSAs required for cleaning and the cost of the end-of-pipe waste treatments. It serves as a direct pollution prevention goal such as removal of phenol and many other harmful wastes that may be present in streams coming out of industrial processes.

Mass-exchange operation is common in industrial processes, a mass exchanger is any direct-contact mass-transfer unit that employs a mass-separating agent (MSA) or a lean phase (such as solvent, adsorbent, stripping agent, ion exchange resin) to selectively remove specific components (pollutants, products, byproducts) from a rich phase (a waste or a product) (Isadfiade, 2008; Hallale, 1998; El-Halwagi, 1997). Mass-exchange operations include absorption, adsorption, stripping, solvent extraction, leaching, and ion exchange. Multiple mass exchange operations can be involved in many industrial situations, and several candidate MSAs may have to be considered especially where there are several rich streams from which mass has to be transferred through the employment of MSAs for the removal of the targeted species. Therefore, applying the mass exchanger networks synthesis approach can provide both technical and economic benefits. In this research, approach of Hallale (1998) and those of Hallale and Fraser (2000a & b) are investigated in the screening and optimising the use of external mass separating agents in the removal of phenol from waste streams.

The MENS problem statement can be stated as follows (El-Halwagi, 1997; Isafiade, 2008; Hallale, 1998):
Available are a number of rich streams and a number of lean streams, otherwise known as the mass separating agents, the requirements are to synthesise a cost-effective network of mass exchangers that can transfer certain materials from the rich streams to the lean streams. Available also are the flow rate of each rich stream as well as the supply and target composition. Also, the supply and target compositions are given for each MSA. The mass transfer equilibrium relations are also made available for each MSA. The flow rate of each lean stream is not given and will have to be calculated

The process MSA is already available on the plant and can be used for the removal of certain materials at a low or no cost (often free).The flow rate of each process MSA available for mass exchange is bounded by the availability in the plant. On the other hand, the external lean stream can be purchased from the market and their flow rates are subject to economic considerations.

The design questions to be addressed in the research include the following; MSAs to be selected, the optimal flow of such MSAs, stream pairings to be selected and the optimal system configuration?

BACKGROUND

The mass exchanger networks analogue of the pinch synthesis method for heat exchanger networks was developed in El-Halwagi and Manousiouthakis (1989) and extended to El-Halwagi (1997). The authors targeted for the minimum MSA required to accomplish a separation task and also presented design methods needed to meet these targets. Hallale (1998) and Hallale and Fraser (2000a & b) developed the $y - y^*$ tools for targeting the mass exchange area and capital cost for both stage-wise and continuous contact columns that were not available in the studies of El-Halwagi and co-worker. One of the important areas of MENS problems which have not been given much attention is the optimal selection of MSAs in MENS when there are multiple MSAs.This constitutes the purpose of this study through the use of the tools developed by the aforementioned researchers in this background.

2.0 METHODOLOTY

Pinch analysis as applied to MENS, involves targeting before actual design which include; minimum mass separating agent (MSA) targeting, the minimum number of units targeting (El-Halwagi, 1997), capital and total cost targeting

(Hallale and Fraser, 2000a & b), then network designs.Hallale, (1998)'s y-y* tool will be employed in solving a problem with multiple external MSAs. The following factors will be used to determine the most suitable MSA to be used; the lowest overall cost of removing mass load of the contaminant, the minimum flow rate required for the selected MSAs, operating cost of the MSAs, capital and total cost targets and also the capital and total costs of the design network will be accounted for to enable proper selection between the multiple external MSAs.

2.1 Mass Separating Agent Targets

Pinch technology strives to optimize the use of the process MSAs to recover mass from the process before employing the external MSAs. If the mass removed with process MSAs is maximized, lesser external MSAs will be required. The pinch diagram approach for targeting the minimum external MSA requirement is an analogy to that of the pinch in HENS.A composite of all the rich streams is obtained by plotting each rich stream containing the mass to be removed against its supply and target compositions on a single graph (Isafiade, 2008). Addition of the mass loads of the rich process streams in the synthesis task in each concentration interval is accomplished and a new line drawn across the interval equivalent to the sum of the mass load (El-Halwagi and Manousiouthakis, 1989). Lean streams were treated the same way using the same steps. Both composite curves were drawn on the same axes as presented by El-Halwagi and Manousiouthakis, and it is shown in Figure 1.

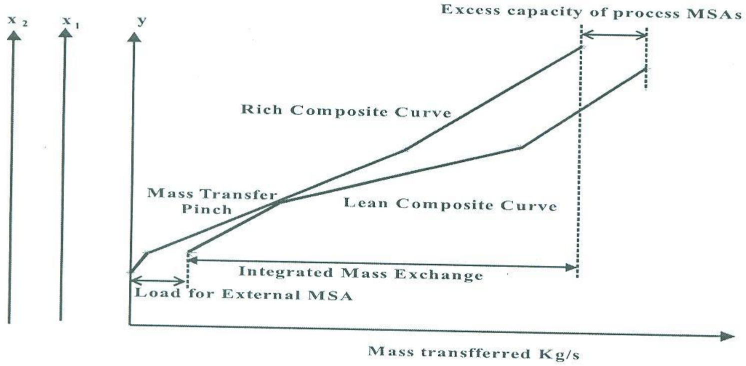

Figure 1: Mass exchange composite curves (El-Halwagi and Manousiouthakis, 1989).

The point at which the rich and lean composite curves have contact is known as the *mass transfer pinch.* The two curves touch each other not because there is zero or no driving force but the value is built into the lean stream compositions using the equilibrium relation shown in Equation (1) (Hallale and Fraser, 1998).

$$y = m_j(x_j + \varepsilon_j) + b_j \qquad (1)$$

where y and x are the rich and lean stream compositions, m_j is the mass transfer equilibrium relation for MSAs, ε_j is minimum allowable composition difference, which is also the driving force and bj is the equilibrium constant.

According to Hallale and Fraser (2000a), for a MENS problem where each lean stream has separate composition scales, it is important to point out that they are not equivalent because of the different equilibrium relations. For all MSA compositions to have a common basis therefore, an MSA composition, x_j, will have to be expressed as the rich stream composition with which it would be in equilibrium, y^*. The equilibrium relations transformation is as follows;

$$y^* = m_j x_j + b_j \quad (2)$$

The driving forces for exchanger sizing is expressed in terms of y and y* values. The minimum composition difference between y and y* is represented as Δy_{min} and is related to the composition difference in the MSA, Δx, through the equilibrium constant. The authors then constructed the lean composite curve in terms of y* values correspond to the x^s and x^t values for the MSAs. Both the rich and lean streams composite curves were then presented on the same axes against mass transfer load and shifted together until a pinch was noted (Figure 2). Plotting lean streams in term of y* values prevented the composite curves from touching at the pinch but now separated by a composition difference of Δy_{min} (Hallale and Fraser, 2000a).

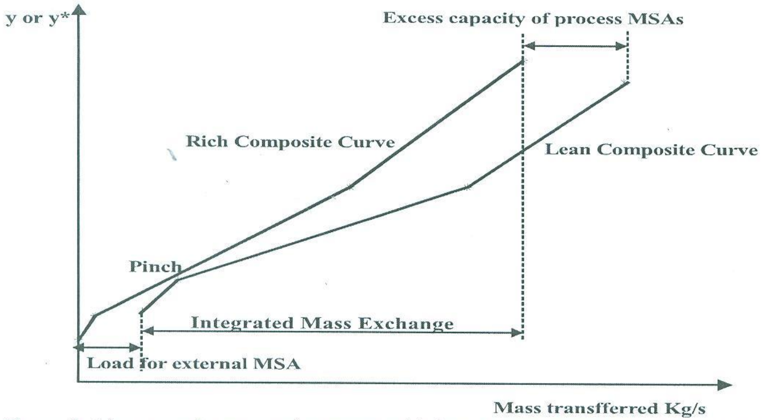

Figure 2: Mass transfer composite curves with lean stream compositions y* (Hallalae and Fraser, 2000a)

The region of complete vertical overlap of the rich composite curve over the lean composite curve in Figure 2shows the optimum amount of species that can be removed by the process MSAs. The overshoot of the lean composite curve over the rich composite curve indicates the excess capacity of the process MSAs that can remove load available. Details of the process is contained in Hallale (1998). The external MSAs flow rate targets is established by drawing y-y* composite curves for these MSAs.

2.2 Capital Costs Targets

To determine the capital cost of a mass exchanger network, factors like the number of mass exchangers, the size, number of transfer unit or number of stages of the exchangers, and the material of construction have to be accounted for as these contribute to the capital cost of a mass exchange network (Hallale, 1998).

2.2.1 Number of Transfer Unit Targets

Targeting for the capital cost of mass exchange networks include factors such as: the target for the number of equilibrium stages in the network, total number of transfer unit, exchanger diameters, transfer height, inactive heights, distribution of units between streams and other relevant information regarding number of staged are contained in Hallale, (1998). The mass transfer composite curves which represent the entire network do not show the composition differences that can be used for the number of transfer unit targetingand to predict equipment sizes. A new plot, y-y* composite curve developed by Hallale (1998) and used in Hallale and Fraser (2000a) which shows the composition differences and still representing the entire network was seen to be useful and will be used in this work. The tool as developed in Hallale (1998) is shown in Figure (3).

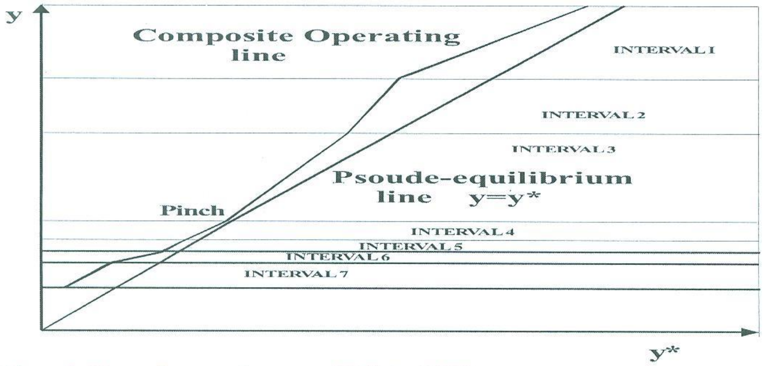

Figure 3: The *y-y** composite curve of Hallale, (1998).

The y-y* composite curve plot developed by Hallale (1998)shows the profile for vertical mass transfer andmanyothermaterialsneededfor mass exchanger sizing. The plot presents the analogy between HENS and MENS using pinch technology. The ratio of the composite operating line slope to the equilibrium line slope is the removal factors A, and the differences between the operating line and the pseudo- equilibrium line is Δy values (driven force). The detail of the tool is contained in Hallale (1998).The number of stages can be determined for each composition interval using graphical approach or Kremser equation for stage wise exchanger while for continuous contact columns transfer unit approach used for the height targeting. In this study, the continuous contact exchanger is used and the minimum network height, *Hmin*, was determined for each interval as follows (Hallale and Fraser 2000b):

$$H_{min} = \sum_{i}^{\text{Rich streams}} HTU_i + \sum_{k \propto i} NTU_i = \sum_i H_i \quad (3)$$

where NTU and HTU are number and height of theoretical units respectively. NTU is a function of Δy_{min} is given as:

$$NUT = \frac{y^{in} - y^{out}}{\left(y_i - y_j^*\right)_{\ logmean}} \quad (4)$$

Δy_{lm} is the log means rich-phase composition differences, given by:

$$\left(y_i - y_j^*\right)_{\ logmean} = \frac{\left(y^{in} - y^{*out}\right) - \left(y^{out} - y^{*in}\right)}{\log\left[\frac{\left(y^{in} - y^{*out}\right)}{y^{out} - y^{*in}}\right]} \quad (5)$$

Δy^{in} and Δy^{out} are driving forces, the differences between the operating line and equilibrium line.

2.2.2 Capital Cost and Total Annual Cost Estimation

Hallale (1998) targeted for total number of exchanger height by summing up the contributions from each rich stream using a method similar to that of shell targeting in HENS (Ahmad and Smith, 1989). Because of the pinch division, the author subdivided the rich stream contributions in to contributions above and below the pinch. The total target as presented by Hallale,(1998) is thus:

$$H_{min} = \sum_{i}^{Rich} H_{i,above\ pinch} + H_{i,below\ pinch} \quad (6)$$

2.2.3 Minimum Number of Unit Targets

The minimum number of units is also required for capital cost targeting for the purpose of practicality and operability. Minimum number of stages is assumed to be achievable in the minimum number of units. The minimum number of mass exchanger N_{unit} is simply one less than the total number of streams in the network as presented by Hallale (1998). For network where there is pinch division, this should be applied to each side of the pinch separately as done by Hallale (1998):

$$N_{units} = (N_R + N_S - 1)_{\ Above\ pinch} + (N_R + N_S - 1)_{\ Below\ pinch} \quad (7)$$

where N_R and N_S are the number of rich process streams and MSAs, respectively.

Capital and total annual cost target are estimated as follows;

$$Capital\ cost\ target\ (cost)_{capital} = \sum_i \sum_j C_{ij} H_{ij} \quad (8)$$

Where C_{ij}, is the annual cost of each column plate and its value depends on the mass exchanger's type and size. N_{ij} is the number of transfer height.

$$Total\ annual\ (cost)_{total} = capital\ cost + operating\ cost \quad (9)$$

2.3 Network Design

In order to meet the MSA cost targets in design, stream matching should start at the pinch since this is the most constrained part of the network (El-Halwagi and Manousiouthakis, 1989). For capital cost targets, Hallale, (1998) recommends that a low number of units should be used to approach as closely as possible the ideal profile. The feasibility criteria applicable to pinch matches presented by El-Halwagi and Manousiouthakis, (1989) and Hallale, (1998):

2.3.1 Stream Population: This recommendation of Hallale (1998) was observed in the stream population technique.

2.3.2 Operating line versus equilibrium line: This was also observed as recommended by Hallale (1998)

2.3.3 The Driving Force (y-y*) Plot

The driving force plot is constructed from the *y-y** composite curve plot as done for MENS in Hallale (1998), the selected matches between rich and line stream is evaluated on the *y-y**composite curve by comparing the operating line of each potential match with the composite operating line.

2.3.4 Remaining Problem Analysis

A selected match is evaluated based on the penalty incurred when the remaining problem is analysed. Penalty means the use of more stages above the target in design, and it is expressed in terms of efficiency, $_{\text{match}}$.

The methodology outlined above is applied to an industrial problem for the purpose of pollution prevention, removal of pollutant from wastes generation by the plant to a satisfactory level in the most economical way and selection of most suitable external MSA for the removal of the pollutant.

2.4

2.5 Problem Specification

This problem specified here involves the removal of phenol from two aqueous streams, R_1 and R_2 by solvent extraction. Removal of phenol from the waste streams is necessary because of its harmful effects when released into nearby streams or rivers. Two process MSAs gas oil (S_1) and lube oil S_2 are available. It is specified in the problem that the entire gas oil stream should be used. Four external MSAs (S_3, S_4, S_5 and S_6) which are activated carbon, ion exchange resin, air and light oil respectively are available also available for phenol removal.

Stream and cost data for the problem are given in Tables 1 and 2, with all compositions in mass fractions. S_1 and S_2 are available free and the cost of the external MSAs are given in Table 2. The annual operating time for the plantwas assumed to be 8600h. The capital cost of mass exchangers for a continuous contact mass exchanger is assumed to be $4245 per year per height (Papalexandri and Pistikopoulos, 1994). The minimum composition difference, Δy_{min} is specified to be 0.001.

Table 1: Rich Streams Data (Isafiade, 2008)

Stream	G (kg/s)	y^s	y^t
R_1	2	0.05	0.01
R_2	1	0.03	0.006

Table 2: Lean Streams Data (Isafiade, 2008)

Stream	L^c(kg/s)	x^s_j	x^t_j	m_j	b_j	Cost($/kg)
S_1	5	0.005	0.015	2	0	0
S_2	3	0.01	0.03	1.53	0	0
S_3	∞	0	0.11	0.02	0	0.081
S_4	∞	0	0.50	0.09	0	2.55
S_5	∞	0	0.029	0.04	0	0.06
S_6	∞	0.0013	0.015	0.71	0.71	0.01

$G_i$in Table 1 is the flow rate of process stream i, y^s_i and y^t_i are the supply and target concentrations (mass fractions) of the pollutants respectively.

L^c is the upper bound on the flow rate of process MSA j, x^s_j and x^t_j are the supply and target concentrations of the MSAs, respectively. m_j is the mass transfer equilibrium relation for MSAs while ε_j is minimum allowable composition difference as earlier mention in this paper.

3.0 RESULTS AND DISCUSSION

3.1 Determination of the Minimum Mass Separating Agent

Hallale (1998) analysed this problem for S_6 scenario using the stagewise column but the problem will now be analysed for all the external MSAs in this paper. In the problem specifications above each lean MSA has its individual composition scales as mentioned in the introduction and are not equivalent due to different equilibrium relations. Then the MSA composition x_i is stated as rich stream equilibrium composition, y*, as expressedin equation (2), this allows all the MSAs composition to be transformed to a general basis as shown in table (3) corresponding scale for y* (Hallale and Fraser. 2000a).

Table 3: Rich Streams Data shown (Δm_i)capacity flow rate

Stream	G (kg/s)	y^s	y^t	Δm_i(kg/s)
R_1	2	0.05	0.01	0.08
R_2	1	0.03	0.006	0.024

Corresponding Scale for y* and process MSAs capacity flowrate

Stream	($L^c{}_j/m_j$)(kg/s)	y^{*s}	y^{*t}	Δm_j(kg/s)
S_1	2.5	0.01	0.03	0.05
S_2	1.961	0.0153	0.0459	0.06
S_3	∞	0	0.0022	-
S_4	∞	0	0.0459	-
S_5	∞	0	0.00116	-
S_6	∞	0.00192	0.01165	-

Following the steps in Figure (2), Mass transfer pinch point was seen to be at y and y* values of 0.0163 and 0.0153 respectively which were the values obtained in the work of Hallale (1998). The minimum external MSA duty is 0.00964kg/s and the excess capacity flow rate of S_2 is 0.0156kg/s. Excess capacity flow rate can be eliminated by lowering the flow rate or the outlet compositions of process MSA. In this case, only the capacity flow rate of the process MSA S_2 was reduced from 1.961 to 1.451kg/s. The target capacity flow rate (L_j/m_j) for external MSAs were determined to be 4.382kg/s for S_3, 0.630kg/s for S_4, 8.31kg/s for S_5 and 0.992kg/s for S_6. The MSAs actual flow rate (L_j) targets are: S_1, 5kg/s, S_2, 2.22kg/s, S_3, 0.0876kg/s, S_4, 0.0567kg/s and S6, 0.704 kg/s.

The first criterion to be considered in screening, of MSAs is their allowable concentration range, both the supply and the target composition. Pinch rule implies that no external MSA should be used above the pinch; that means y^{*pinch} 0.0153 is the target composition for all the MSAs. MSA with target composition below this is thermodynamically feasible; MSA with supply composition below pinch but target composition above can be reduced to pinch composition. While MSA with supply composition above pinch, composition is thermodynamically and economically inferior. In this problem S_3, S_5 and S_6 have target composition below pinch 0.0022, 0.00116 and 0.1165 respectively, while S_4 with 0.0459 target composition was reduced to y^{*pinch} 0.0153, which is corresponding to 0.17 x_4 values.

The second criterion for selecting MSA is based on the cost of removing 1kg of mass load of phenol, which depends on both the cost of the MSA and its allowable concentration range as follows (Fraser et al. 2005).

$$\text{Cost of removing mass load } \left(C_j^r\right) = \frac{\text{Cost of the MSA } \left(C_j\right)}{\left(y_j^{*target} + y_j^{*supply}\right)}$$

The removal cost of the MSAs S_3, S_4, S_5, and S_6were calculated to be: \$0.730kg, \$0.736kg, \$1.5kg and \$2.069kg respectively.

Also, operating cost is another criterion for screening external MSAs, the flow rate of MSAs can be used to determine their minimum operating cost (MOC) as follows:

$$\text{Operating cost, } [\text{cost}]_{\text{operating}} = \text{cost of MSA} \times \text{flow rate} \times \text{operaring hours}$$

For 8600 operating hours per year, S_3MOC was determined to be \$219,680yr, \$447,635yr for S_4, 617,466for S_5, and \$217,958yr for S_6.

3.2 Capital and Total Cost Targets

Capital cost targets were estimated for all the MSAs using the target for the number of transfer unit (NTU)in the network (Equations 4 and 5).In this problem specification, the cost of the exchanger had been given, thus, there is no need for targeting for the height of theoretical units (HTU).The number of transfer unit for each MSA is represented on a grid diagram in Figure (4). Notice that Figure 4d was similarly obtained in Hallale (1998) which implies that the method is correctly applied in this study. The intervals are represented as the vertical line with pinch marked with a dotted line. The rich streams are shown running from right to left on the diagram, while the lean streams run from left to right with their corresponding compositions as shown in the figures below.

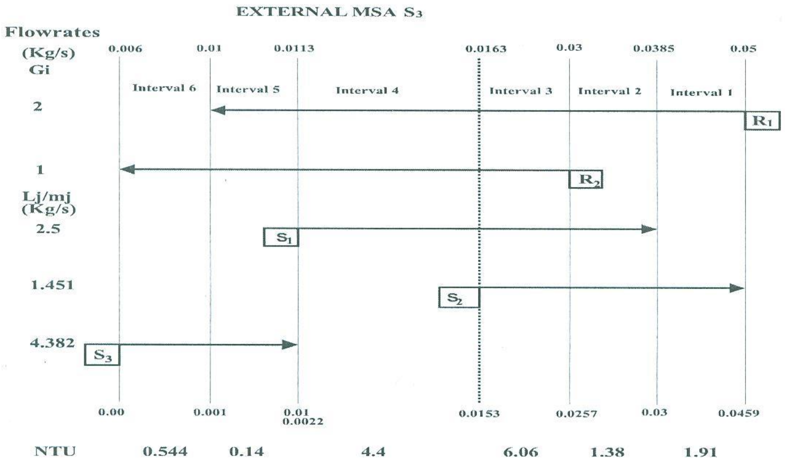

Figure 4a: Grid diagram showing external MSA S_3

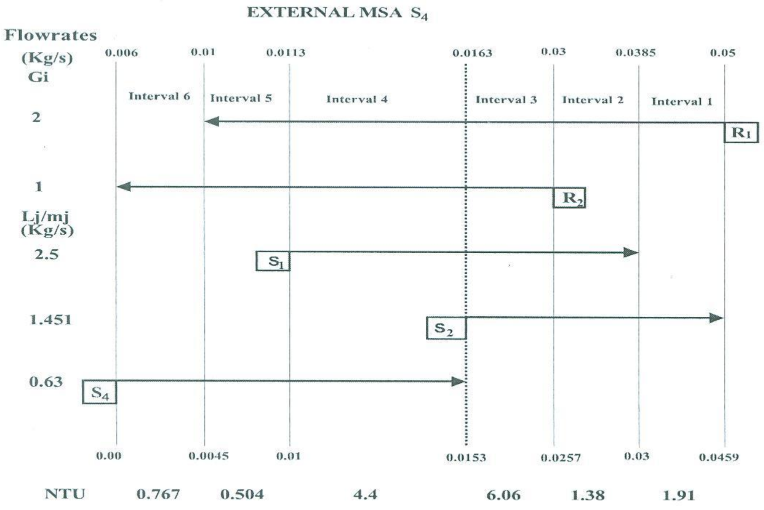

Figure 4b: Grid diagram showing external MSA S_4

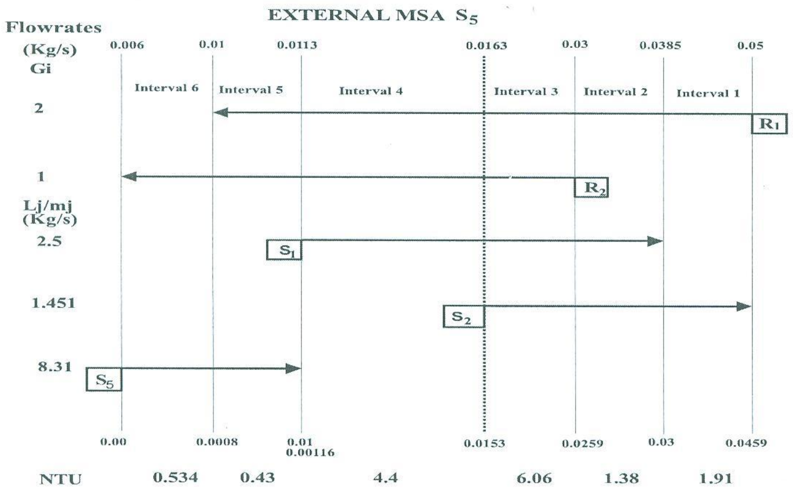

Figure 4c: Grid diagram showing external MSA S_5

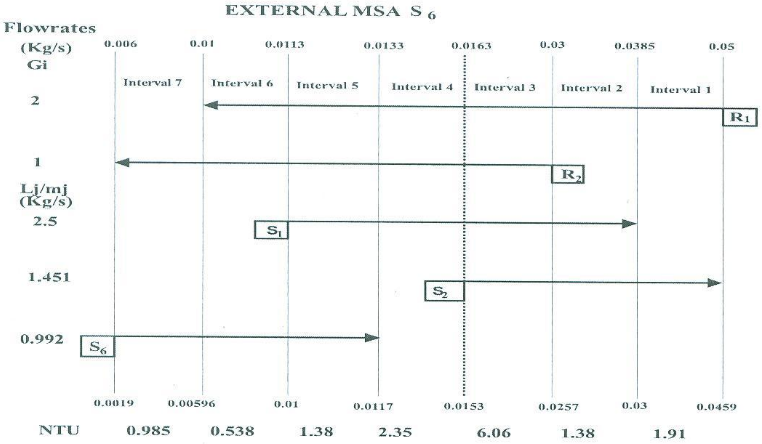

Figure 4d: Grid diagram showing external MSA S6.

The targets for the total number of units for all MSAs were obtained by summing up the contributions from each rich stream using Equation (6).The total number of units targeting for the MSAs are: for S3, 27, S4, 26, S5, 27 and S6, 26.

3.3 Targeting for Minimum Number of Mass Exchanger Units(N_{unit})

Targeting for minimum number of mass exchanger unit, capital and total annual cost target are estimated using Equations (7) (8) and (9), respectively in manners similar to that of Hallale (1998). The results are shown in Table (4) as follows:

Table 4: Capital and Total Cost Targets

MSA	Capital cost ($/yr)	Total cost ($/yr)
S3	110,370	330,050
S4	114,615	562,250
S5	110,370	727,836
S6	114,615	332,525

3.4 Network Design

The whole network design is obtained by combining the designs in the two regions using the feasible criteria and the techniques of Hallale (1998), these were used to obtain the minimum MSA target, the number of units and the corresponding capital costs of the networks. The network designs are presented in Figures 6a to d, matches between streams connected by vertical lines represent the exchangers. Figure 6d was similarly obtained where Hallale (1998) applied the tool to S6. The number of units for each match was calculated using Equation (4 and 5) and the total number of units for each design is the sum of the number of units for each match as shown in Table (5).

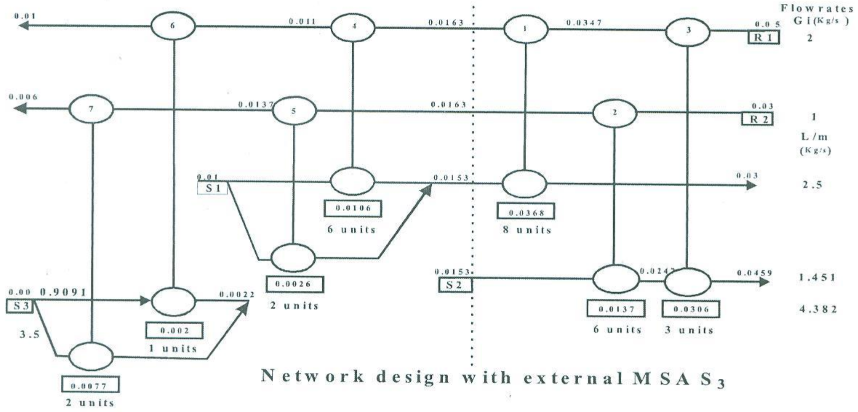

Figure 5a: Network design featuring external MSA S_3

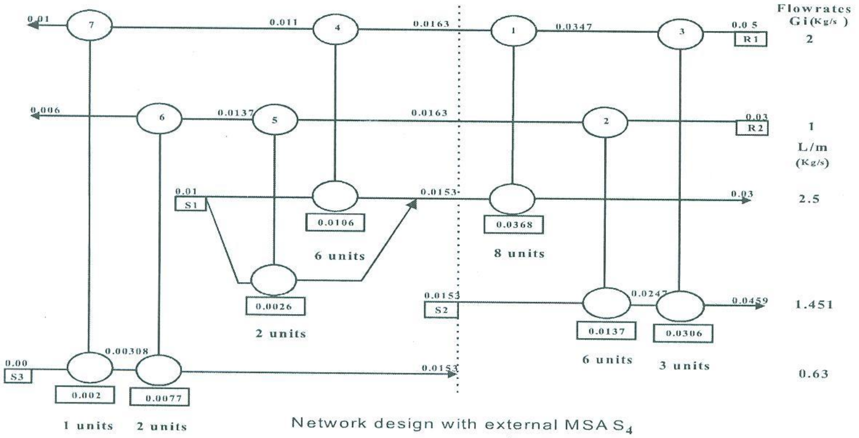

Figure 5b: Network design featuring external MSA S_4

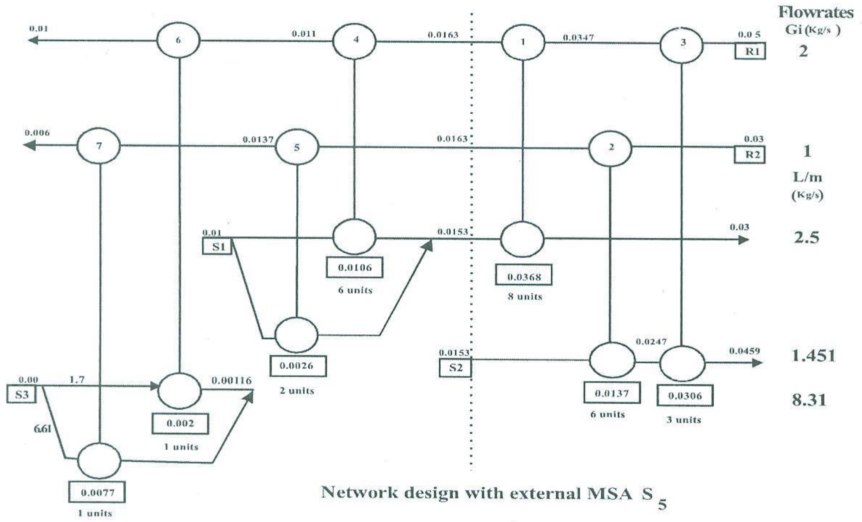

Figure 5c: Network design featuring external MSA S_5

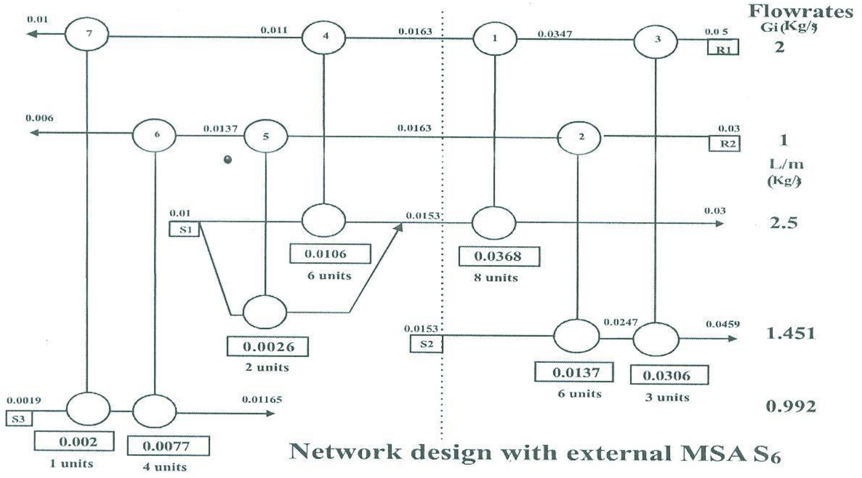

Figure 5d: Network design featuring external MSA S_6

The total number of units used in the actual design are; 30, 28,28 and 27units for S_3, S_4, S_5 and S_6 respectively. Capital cost and total annual cost for the networks design, were estimated using the same approaches for targeting (Table 5);

Table 5: Capital and Total Cost of Networks Design

MSA	Capital cost ($/yr)	Total cost ($/yr)
S_3	118,860	338,540
S_4	118,860	566,495
S_5	114,615	732,081
S_6	127,350	345,310

The table (6) below gives the summary of the MSAs; the cost of each MSAs, removal cost of 1kg of phenol, the flow rates, capital cost and total annual cost targeting and networks design and their discrepancies

.

Table 6: Summary of the MSAs details

MSA	MSA Cost ($/kg MSA	Removal Cost ($/kg phenol	Flow Rat (kg/s)	Operating Coast ($/y	Target TAC	Actual TAC	Discrepancy Target/Actua	Discrepanc MSAs
S_3	0.081	0.736	0.0876	219,680	330,525	338,540	+2.6%	0.00%
S_4	0.255	1.5	0.0567	447,635	562,250	566,495	+0.76%	67.3%
S_5	0.06	2.069	0.3324	617,466	727,836	732,081	+6%	116.2%
S_6	0.01	0.730	0.704	217,960	332,525	345,310	+3.8%	2.0%

From the detailsanalysesin the table (6) above, for the cost of each MSA that can remove 1kg of phenol and their minimal operating cost MOC, S_6 with the smallest MSA cost of $0.01kg has the lowest removal cost and MOC of $0.730kg and $217,960yr respectively. Followed by S_3 with MSA cost of $0.081 has $0.736kg and $219,680yr. S_4 with MSA cost of $0.255kg has $1.5kg and $447,635yr, while S_5 with $0.06kg has $2.069kg and 617,466yr, respectively. These results show S_6 with the cheapest cost of MSA to have the lowest removal cost and MOC. S_5 the second cheaper MSA has the highest removal cost and the MOC of about 183.4% and 183.3% respectively while S_4 with the highest cost of MSA has 105.5% and 105.4% of removal cost and MOC respectively, was discovered to be better and preferable to S_5. The Screening and selection of suitable external MSA for this particular problem based on the removal cost and MOC of the MSAs as analysed above, S_6 is preferable followed by S_3 with removal cost and MOC of 0.6% and 0.8% respectively above S_6.

Total annual cost (TAC) was another criterion used for ranking external MSAs which is a function of the operating cost and the capital cost of the mass exchangers used in the design. For this problem specification, TAC of the MSAs S_3, S_4, S_5 and S_6, were calculated to be 338,540, 566,495, 732,081, and 345,310($/yr) respectively. From these results, S_3 has the lowest TAC, followed by S_6 with 2.0%, S_4 with 67.3% and S_5 with 116.2% respectively above S_3.

4.0 CONCLUSION

In this study, pinch technology using the graphical approached together with y-y* tool had been employed in solving MENS problem with multiple external MSAs in order to determine the most suitable and economical external MSA for the removal of phenol from the rich streams below the pinch point. From the results of this study, it can be concluded that selection of external MSA to be used for MENS problem with multiple MSAs should not be based on the MSA with lowest cost. Although S_6 with the lowest cost of MSA was found to be the cheapest based on the removal cost and the minimum operating cost of the MSA while S_5 with lower cost was discovered to be the most expensive among all the external MSA. It can also be inferred from the analysis of the results that the selection of MSA should be better based on the TAC of the network design as capital cost of the network also contribute significantly to the TAC. This can be deduced from the TAC of S_3 which was more expensive among the MSAs but was discovered to be thelower TAC at the end of the network design.

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