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MATLAB Model for designing mass exchange networks: A case study on pyrolysis plant for effective waste minimization

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 Pinch analysis;
 Number of plates

Abstract Enormous amounts of raw materials are consumed through various industrial processes worldwide. Vast amounts of raw materials utilized by the chemical industry typically go to waste. Mass integration is a distinctive method of streamlining the consumption of raw materials in chemical industries. Mass integration was developed by employing principles of pinch analysis in order to optimize mass exchange networks. To apply the concepts of mass integration, this work introduces a Matrix Laboratory (MATLAB) code designed on the bases of the composition driving force graphical design approach. This MATLAB code was devised to analyze details of mass transfer operations with the lowest number of calculations possible. The algorithm's detailed coding allows for designing mass exchange networks above and below the pinch. For maximum mass recovery, pinch principles were employed, and were delivered in an educational manner to students and young researchers in the field. The MATLAB code was designed to develop a useful toolbox for process integration as well as determine the number of plates required for each mass exchanger. The model was tested at pyrolysis plant with the aim of achieving mass targets and optimum matches for maximum recovery at the lowest costs possible.

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1. Introduction

Due to the rapid rise in prices of raw materials and the adverse financial and environment consequences of material waste, proper management and utilization of such raw materials

has become more crucial with time. This has led researchers to investigate all possible solutions/pathways that may help alleviate the problem of the enormous quantities of wasted raw materials in the chemical industry.

Mass integration is an efficient management technique that allows for optimized consumption of raw materials and the minimization of the adverse effects material waste on the environment. Typically, mass integration is used to strip a discarded stream of pollutant material and reduce environmental contamination, or to select certain by-products from a product stream and maximize quality. Either

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way, applying concepts of mass integration to such industrial processes is both environmentally and economically beneficial. Mass integration enhances process performance by accomplishing mass targets, reducing the external usage of MSA and waste discharge. It employs the fundamentals of pinch analysis in order to minimize loss of raw materials and products and achieve targets. Basic pinch principles were originally introduced by Linhoff [1].

The use of mass exchange networks (MENs) have been detailed extensively in the literature [2]. Over the years, different strategies towards designing effective MENs have typically fallen into three main approaches. The first of these approaches, the insight-based pinch and graphical approach was originally introduced by El-Halwagi and Manousiouthakis, who aimed to address the problem of mass-exchange bottlenecks as well as mass exchange network synthesis [2]. The same researchers addressed the problem of automatically synthesizing mass-exchange networks in which the mass of a single component was exchanged between a set of rich streams and a set of lean streams [3]. They also developed systematic procedure for the simultaneous synthesis of primary transfer mass-exchange networks and their associated mass-exchange regeneration networks [4]. Hallale and Fraser focused their work on determining capital and total cost targets for MENs [5,6]. The same group of researchers then worked to design MENs that achieved mass targets with the aim of expanding their applications to include multiple mass separating agents (MSAs), transfer of multiple components, regeneration of one of the MSAs, and reactive mass exchange with non-linear equilibrium relationships [7,8]. Gadalla developed a graphical approach to mass network synthesis that was designed to assess the performance of existing MENs against the principles of pinch analysis [9]. Farrag et al. developed a new graphical representation of mass exchange network synthesis, graphing the strength of the driving force between streams for better analysis of process dynamics [10]. Their work provided an insight for the relative mass transfer units for a certain MEN according to the relative position of the exchanger to the equilibrium line and its relative length. For exchangers with approximately equal length as they approach the equilibrium line, the number of trays required increased rapidly. It also highlighted the feasible design regions to perfectly locate the exchangers with minimum mass losses and minimum cost. Mass exchangers using external MSAs are to be only designed below the pinch. Similarly, process lean streams should dispose their excess mass load into the environment above the pinch [10].

The second approach to the design of MENs involves mathematical-based optimization models. Papalexandri and Pistikopoulos proposed a multiperiod MINLP model for the synthesis of flexible heat and mass exchange networks based on an integrated hyperstructure representation [11]. Szitkai et al. developed a linear, superstructure optimization model for the synthesis of MENs, where the linear character of the model was preserved by considering single-component mass exchange network synthesis and packed columns as mass exchangers [12]. Devoting their work to MEN synthesis problems, Chen and Hung designed a mathematical programming approach based on the stage-wise superstructure representation of MENs [13,14]. Liu et al. presented a systematic approach to overall combined mass and heat exchanger network synthesis. They proposed the incorporation of bypass

streams and the simultaneous synthesis strategy to further improve upon previously reported methods [15,16]. Velázquez-Guevara et al. proposed a strategy for the modelling and optimization of MENs, basing their work on the use of a state task-network superstructure which they modelled through the use of general disjunctive programming [17].

The last approach to the design of MENs is called a 'hybrid' approach which involves combining or integrating different design approaches. This approach may be exemplified by the works of El-Halwagi and Manousiouthakis [7,8] and other researchers. Short et al. designed detailed mass exchange network models using a novel combination of MINLP topology optimization based on shortcut models paired with a rigorous NLP individual unit optimization [18]. Azeez et al. developed new superstructures for the optimization of total annual costs in HENS and MENS [19]. Their work presented mathematical formulations for optimizing the TAC for HENS and MENS and provided network structure to represent all matches.

All aforementioned studies aimed to reduce raw-material waste and provide maximum protection to the environment. Researchers typically worked to reduce the utilization of fresh resources whilst basing operations on the pinch diagram, thus achieving optimal matches between rich and lean streams without violating thermodynamic limitations.

The current work built upon a graphical methodology that had been designed to assess differences in compositions of target material in the rich stream (y) and equivalent lean stream (x_{eqv}) versus its composition in the equivalent lean phase (x_{eqv}). In this approach, composition driving force (CDFs) are plotted on a new separate axis in order to synthesize, analyze and evaluate the performance of MENs against datum lines and other design limitations [20]. This approach was designed to provide a clear process of analysis to the designer that would facilitate user interaction and thus help easily identify process bottlenecks. The CDFs were set as the main drivers that control material transfer of target materials from richer to leaner streams, and help postulate the number of theoretical plates. Composition driving forces affect total costs and their assessment would be beneficial in screening matches, they couldn't however be used for targeting. Still, this CDF representation approach has been valuable in sizing mass exchanger equipment. It addresses limitations to simultaneous synthesis and network design of MENs. This approach targeted minimum MSAs, located the pinch point, and simultaneously designed the network to achieve mass targets. Even though this approach facilitates the representing of mass networks, it is both difficult and time-consuming to plot each exchanger manually when dealing with large MENs. Thus, plotting exchangers using computer programming, such as with the use of MATLAB, would greatly reduce time and effort.

This paper presents a simple algorithmic approach to the design of MENs and the verification of the size of each mass exchanger by calculating the number of plates required. Our model was designed to apply pinch principles as an extension to the graphical design approach introduced above [10]. In our method, the graphical and algebraic approaches are complementary. The aforementioned graphical method relies difference in composition between lean and rich streams, and illustrates the mass exchanger units on a graph where each unit is expressed as a straight line. It is essential to predetermine pinch compositions through standard pinch analysis.

El-Halwagi developed a mass-exchange pinch diagram to represent both the rich and lean composite streams and the maximum amount of the transferrable component that could be transferred. The author defined the point where the two composite streams touched to be the pinch composition for this process [21].

In the coming section, this work's algorithm is explained in a step-by-step format to extend the benefit to students and novice researchers and assist them in developing a general code using MATLAB. Through such a code, the composition of the rich and lean streams can be integrated, the network developed, and the number of plates determined directly from the code generated without the need for additional computations.

2. Methodology

2.1. Theoretical foundation and methodological framework

The CDF graphical approach details describe MENs by plotting a graph of the differences in composition of species in the rich and lean streams and the equivalent composition in the lean streams [20]. This approach relies on targets previously obtained through the application of pinch analysis [21].

The composition of the equivalent lean stream is plotted on the x-axis and is calculated as shown in Eq. (1).

$$x_{eqv} = m(x + \varepsilon) + b \quad (1)$$

where (ε) is the minimum difference in composition, (m) is the equilibrium constant.

The difference in composition between both streams is symbolized by ΔC and plotted on the y-axis as described by Eq. (2).

$$\Delta C = y - x_{eqv} \quad (2)$$

As illustrated by Fig. 1, all rich streams are plotted as 45° inclined parallel straight lines, and all lean streams as parallel vertical lines. Each stream is represented by two compositions i.e., supply and target compositions that limit the area of mass integration and defines its boundaries.

Pinch compositions, the equilibrium line for mass transfer (that represents the absolute thermodynamic driving force) and the feasible line (that represents the least driving force between streams and is plotted parallel to the equilibrium line with constant ε) provide some distinguishing design regions for the design insights as shown in Fig. 2. Placing the mass exchanger within the feasible regions ensures minimum mass losses in the process and thermodynamic feasibility of the mass exchanger as shown in Fig. 3. All these constraints were set as clear functions within the MATLAB model. Farrag et al. previously found a relationship between the slope of each mass exchanger and the flowrates of rich and lean streams as expressed in Eq. (3) [20]. In the model, the slope-line equation of each mass exchanger unit plotted within two compositions is inserted to determine the amount of mass integrated within each exchanger. Consequently, the optimal number of plates required for each unit is calculated from the algorithmic approach using the predefined functions. The number of plates from the graphical approach is determined from the plot itself by counting the number of stages of each exchanger as presented in Fig. 4. However, for complex networks, it would be hard to draw the stages for each line on the network. It is thus very

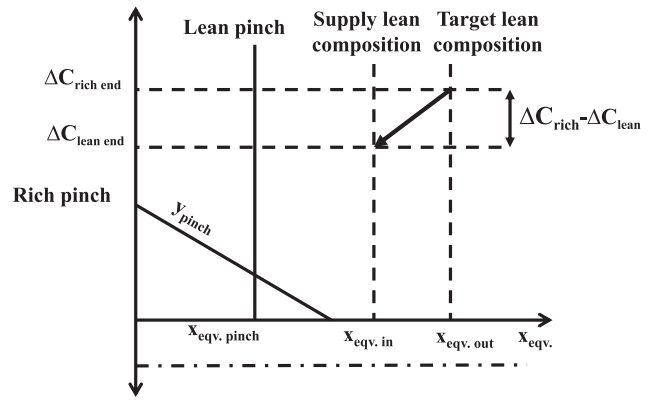


Fig. 1 Single mass exchanger representation on CDF plot [10].

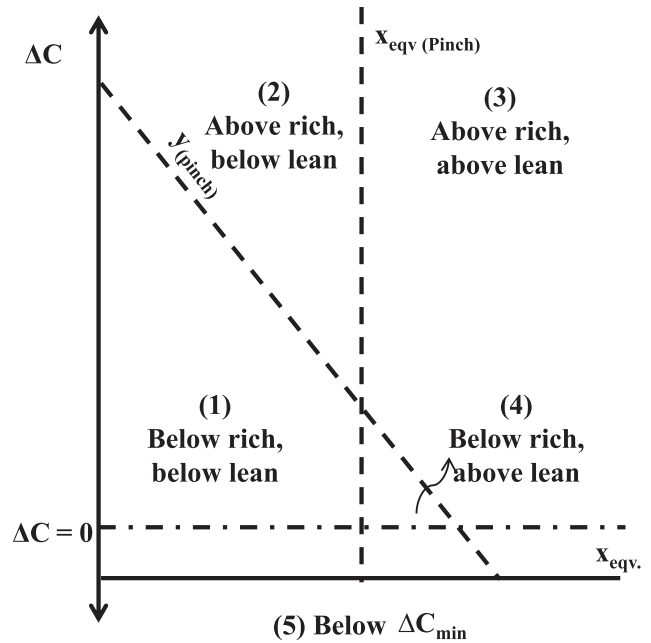


Fig. 2 Characteristic regions useful for MENs design [10].

constructive to calculate it directly from an inserted function as proposed in the algorithm and postulated in Eq. (4). Finding the number of plates controls the size of each unit which limits capital costs.

$$\text{Slope} = \Delta y / \Delta x = L / G \quad (3)$$

$$NTP = \frac{\ln \left[\frac{1}{S+1} \left(\frac{S \Delta y}{\Delta C_{lean} + m \varepsilon} \right) + S + 1 \right]}{\ln(S+1)} \quad (4)$$

where S is the slope of the exchanger line on the Composition Driving Force plot and ΔC_{lean} is the lean end composition driving force.

2.2. The algorithmic approach-grassroot design

Steps for the graphical design of MENs follow a 2-stage procedure: network design above the pinch and network design below the pinch. Pinch compositions are pre-determined from

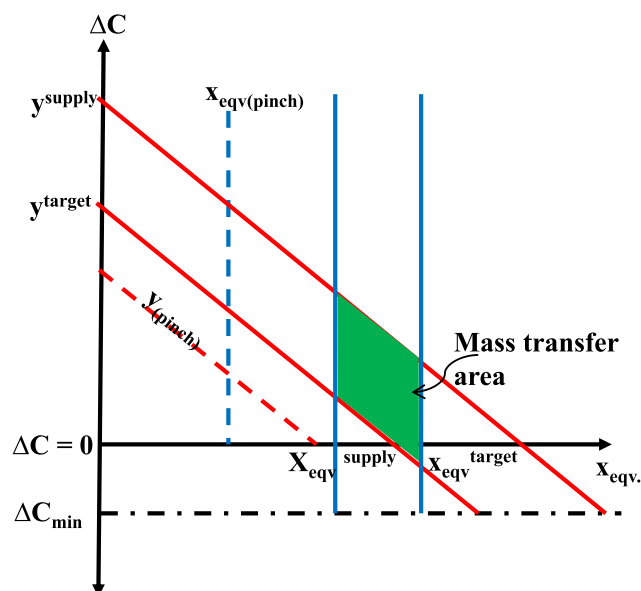


Fig. 3 Constructing mass exchange network on CDF plot [10].

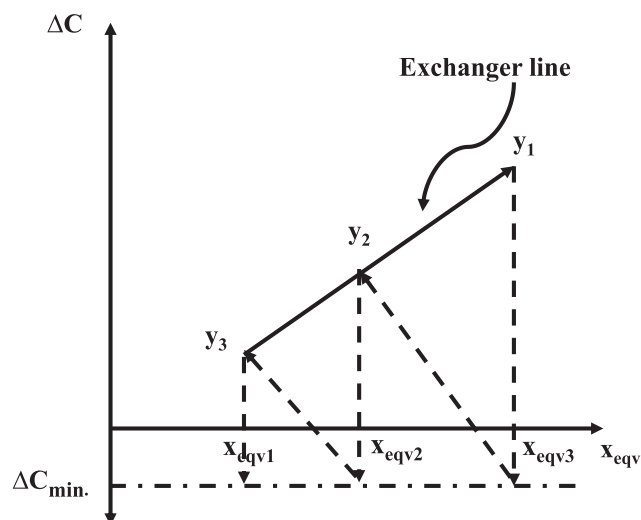


Fig. 4 Graphical determination for the number of plates [10].

standard pinch diagrams and then embedded into the algorithm directly as inputs. Supply and target compositions of both rich and lean streams and flowrates are inserted at the beginning of the model. Then, the equivalent lean compositions are calculated as functions of the lean compositions.

2.2.1. The algorithmic approach – Above the pinch compositions

Fig. 5 depicts the loop structure used to design the network above the pinch points. The following steps should be followed:

1. Insert rich stream with lowest target composition (R_t), the highest supply composition for the rich stream (S_s) and the pinch compositions $x_{eqv. pinch}$ and y_{pinch} .

2. Start with the intersection point between the target composition of the rich stream (R_t) and the supply composition of the lean stream (S_s).
3. If the target composition of the rich stream is below the pinch, then start from the intersection between the pinch line (y_{pinch}) and the supply composition of the lean stream (S_s).
4. If the supply composition of the lean stream is below the pinch, then start from the intersection between the pinch line ($x_{eqv. pinch}$) and the target composition of rich stream (R_t).
5. If target composition of rich and supply composition of lean streams are located below the pinch, then start from the intersection between the pinch points ($x_{eqv. pinch}$, y_{pinch}).
6. Check if $(\frac{L}{m} \leq G)$, then skip this match and select another match.
7. If $(\frac{L}{m} \geq G)$, start to draw a line with a slope $(\frac{L}{mG} - 1)$.
8. If the supply composition of the rich stream is reached first, then the rich stream is stripped off from the targeted material completely, and the lean stream exits at an intermediate composition.
9. If the target composition of the lean stream is reached first, then the lean stream vanishes completely without stripping off all the targeted material from the rich stream, and the rich stream exits at intermediate composition.
10. In case that the lean stream had stripped off all the targeted material from the rich stream and there are no more rich streams in the process, then the remaining MSA is sent to the environment.

2.2.2. The algorithmic approach – Below the pinch compositions

Fig. 6 depicts the loop structure for designing the network below the pinch points. The following procedures should be followed;

1. Insert the lean stream with the highest target composition (S_t), the highest supply composition of the rich stream (R_s), and the pinch compositions $x_{eqv. pinch}$ and y_{pinch} .
2. Start with the intersection points between the target composition of the lean stream (S_t) and the supply composition of the rich stream (R_s).
3. If the supply composition of the rich stream is above the pinch, then start from the intersection between the pinch line (y_{pinch}) and the target composition of the lean stream (S_t).
4. If the target composition of the lean stream is above the pinch, then start from the intersection between the pinch line ($x_{eqv. pinch}$) and the supply composition of the rich stream (R_s).
5. If both target compositions of rich and supply composition of lean streams are above the pinch, then start from the intersection between the pinch points ($x_{eqv. pinch}$, y_{pinch}).

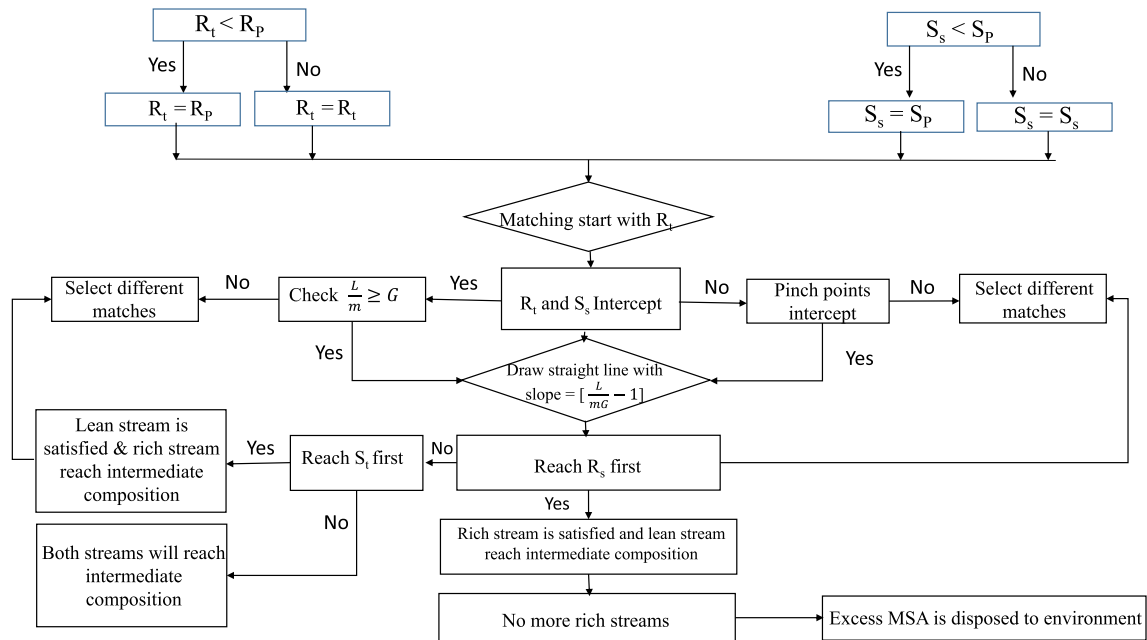


Fig. 5 Loop structure above the pinch.

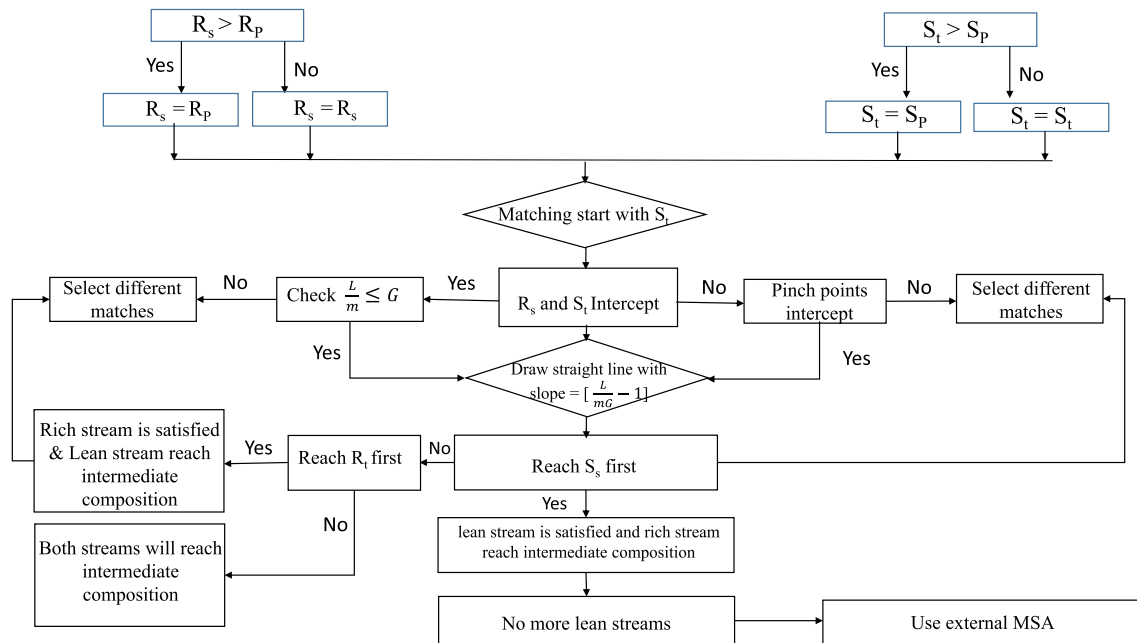


Fig. 6 Loop structure below the pinch.

6. Check if $(\frac{L}{m} \geq G)$, then skip this match and select another match.
7. If $(\frac{L}{m} \leq G)$, start to draw a line with a slope $(\frac{L}{mG} - 1)$.
8. If the supply composition of the lean stream is reached first, then the lean stream had vanished completely without stripping off all the targeted material from the rich stream, and the rich stream exits at intermediate composition.
9. If the target composition of the rich stream is reached first, then the rich stream has had the targeted material stripped off completely, and the lean stream exits at an intermediate composition.
10. If all process lean streams had been used up but there was still targeted material that needs to be stripped off from rich streams, then external MSA should be considered for mass integration.

2.3. Summarized MATLAB code for mass network design

1. The code starts by inserting the following input data: the supply and target compositions of the rich and lean streams; the flow rates of both rich and lean streams; the slopes of each lean stream; the minimum allowable composition difference and the pinch compositions.
2. All the rich and lean streams and equilibrium datum lines are plotted.
3. The plot is divided into two regions: one above and one below the pinch.
4. A number of pre-set conditions are applied upon choosing the suitable interception to start the matching between the rich and lean streams for the regions above and below the pinch using the (if) function.
5. Dependent upon the results of (4), all intersection points for the lean and rich streams above and below the pinch are determined.
6. The starting point is determined from the solution computed by MATLAB.
7. The slope of the exchanger line is calculated from the inserted equation of the slope i.e. $(\frac{L}{mG} - 1)$.
8. The exchanger line is first plotted from the selected starting point to its maximum x and y values.
9. The “for” loop in the MATLAB then determines the interception point that would be reached by the exchanger line.
10. The exchanger endpoint is selected and plotted with its coordinates (x, y) and the line is replaced with an arrow.
11. The mass load and the number of theoretical plates for the exchanger are calculated.

Figs. 7 and 8 summarizes the MATLAB code structure.

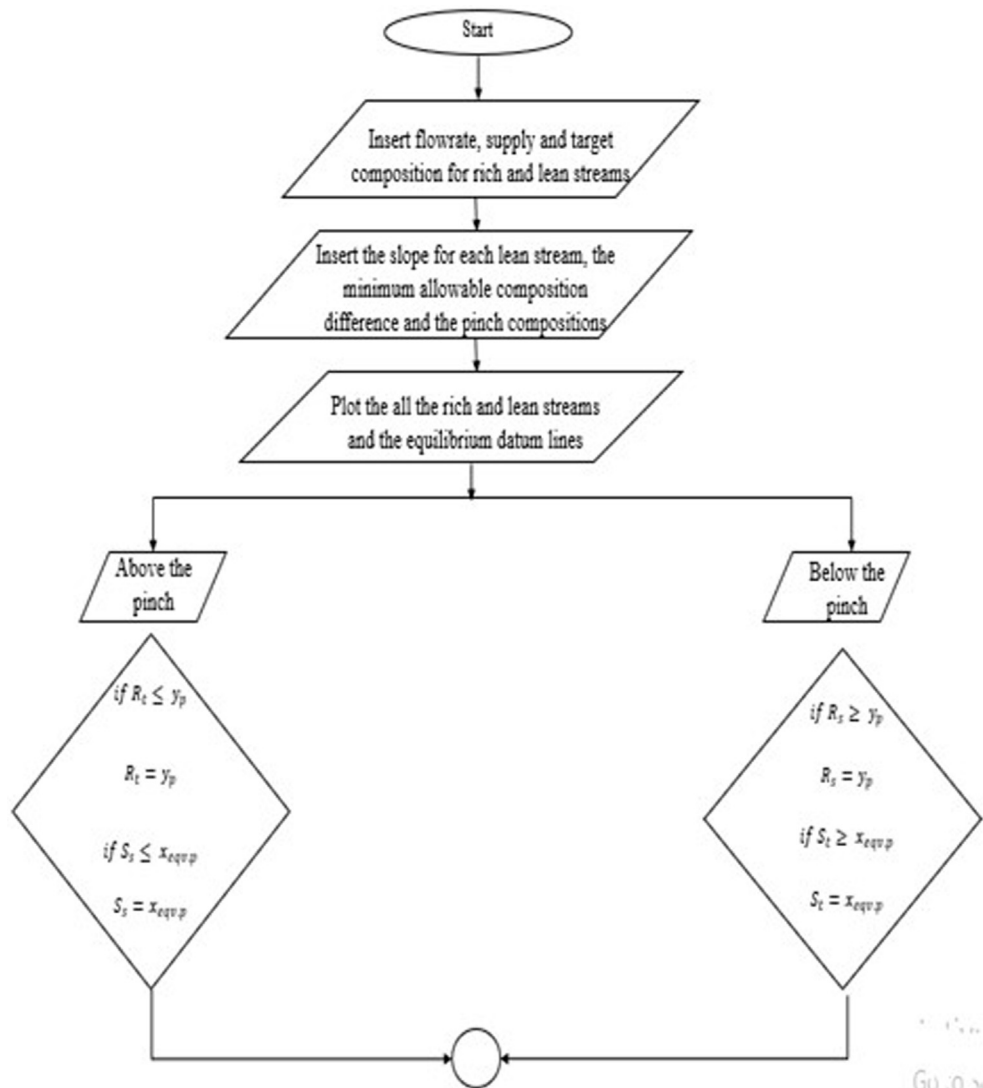


Fig. 7 Summarized flowchart for the Matlab code.

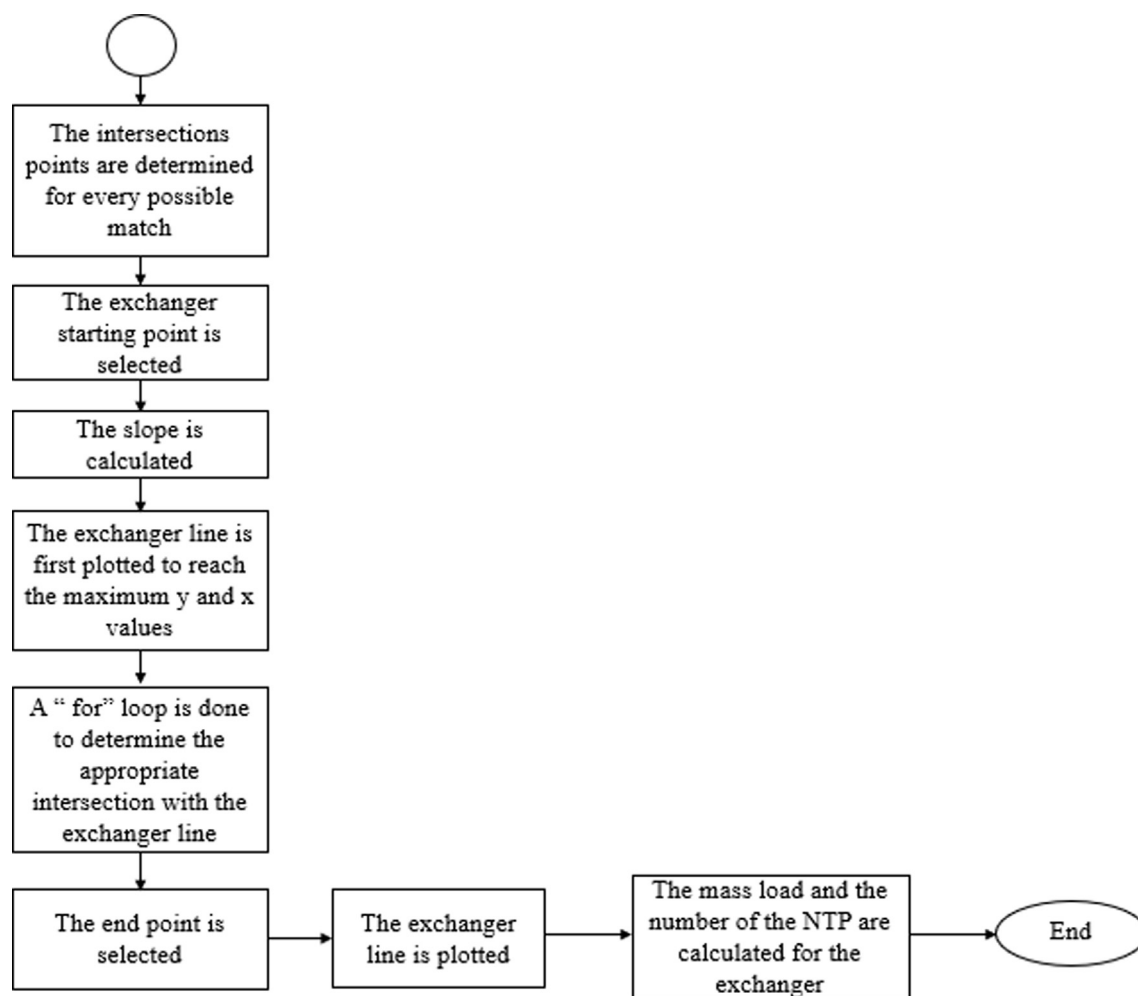


Fig. 8 Summarized block diagram for the Matlab code.

3. Results and discussion

3.1. Application of the algorithmic model to a real case study

In our real case study, scrap tires were converted into fuel in a pyrolysis plant at a processing facility. The process had one rich stream; the wastewater stream (R_1), one process lean stream; the flare gas stream (S_1), and three external mass separating agents; the solvent extractant (S_2), the adsorbent (S_3), and the stripping agent (S_4) [21]. Table 1 shows details pertaining to the different streams.

The pinch points were inserted directly into the model, which had a rich stream pinch composition of 200 ppmw, as well as into the other lean streams. Fig. 9 represents the MEN designed for the pyrolysis process as plotted by MATLAB. The model solved all linear equations of the streams, identifying all possible interceptions and creating four feasible matches presented as mx_1 , mx_2 , mx_3 , and mx_4 .

Above the pinch, S_1 and S_2 were both available for the integration of mass with R_1 . The first mass exchanger integrated mass between R_1 and S_1 and the design started from the intersection between the process pinch points because S_1 started at

Table 1 Pyrolysis process data [20].

Stream	Description	Flowrate, (kg/s)	Supply composition (ppmw)	Target composition (ppmw)	m_j	ε_j
R_1	Wastewater stream from decanter	0.2	500	50	–	–
S_1	Flare gas stream	0.15	200	900	0.5	200
S_2	Solvent extractant	∞	300	1000	1	100
S_3	Adsorbent	∞	10	200	0.8	50
S_4	Stripping agent	∞	20	600	0.2	50

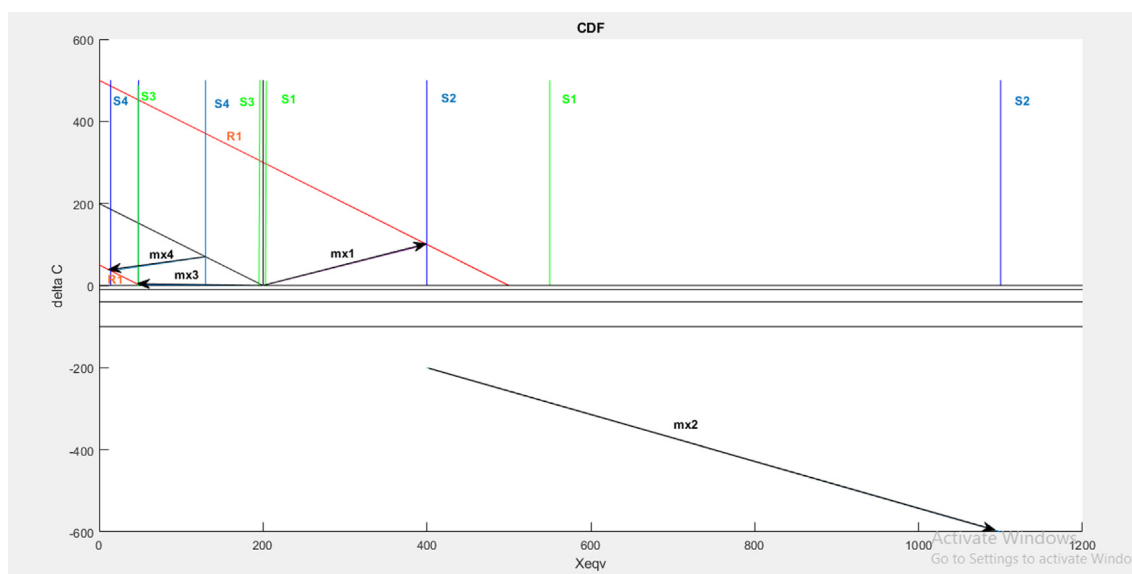


Fig. 9 Pyrolysis process network on Matlab.

Table 2 Summary of the pyrolysis plant.

	mx ₁	mx ₃	mx ₄
y _{in}	500	200	200
y _{out}	200	50	50
L (kg/s)	0.15	0.1579	0.05172
G (kg/s)	0.2	0.2	0.2
M	0.5	0.8	0.2
E	200	50	50
x _{eqv. in}	200	48	14
x _{eqv. out}	400	200	130
ΔC _{rich}	100	0	70
ΔC _{lean}	0	2	36
S	0.5	−0.01316	0.2931
Θ	223.61	152	152
ΔM	60	30	30
No. of plates	3	5	3

the pinch ($x_{eqv.pinch}$). The first mass exchanger line (mx₁) was thermodynamically feasible. It intercepted with the supply rich

stream, indicating that all the waste mass load in the rich stream was removed by the process lean stream (S₁) without being fully consumed. However, the second mass exchanger line (mx₂) violated thermodynamic limitations and pinch principles as well. It had a negative slope and was located in an unfeasible design area. Additionally, the rich stream was already satisfied (stripped totally from the targeted material) from the previous match with the process lean stream (S₁), so there was no need for an external MSA above the pinch.

Below the pinch, S₃ and S₄ were similarly available for the integration of mass with R₁. The third mass exchanger line integrated mass between R₁ and S₃ below the pinch. The design started at the intersection of process pinch points and was extended until reaching the intersection between R_{1target} and S_{3supply}; endpoint of the exchanger line. The third mass exchanger line (mx₃) was thermodynamically feasible; its slope was −0.01316. The flowrate for the external mass separating agent (adsorbent, S₃) was equivalent to 0.157 kg/s. The fourth mass exchanger line (mx₄) was also available below the pinch, allowing for the mass integration between R₁ and S₄. Plotting mx₄ started at the intersection of y_{pinch} and S_{4supply}. The line of this exchanger was extended till it hit its endpoint at the inter-

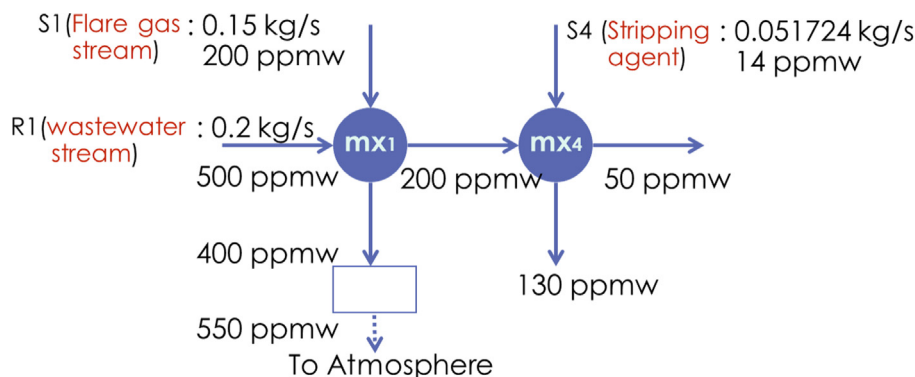


Fig. 10 Mass exchanger units for the pyrolysis process.

section between $R_{1\text{target}}$ and $S_{4\text{supply}}$. This exchanger was thermodynamically feasible; its slope was 0.2931. The flowrate for the stripping agent (S_4) was equivalent to 0.0517 kg/s. The length of each mass exchanger straight line was given as (θ) which was directly proportional to the amount of mass transferred within each exchanger [20].

Table 2 details all outputs of the MATLAB model (attached in the appendix below). Results obtained from this model are evidently match those obtained using the graphical method as reported by Farrag et al. [20].

3.2. Model validation

As aforementioned, both S_3 and S_4 were available below the pinch for mass exchange with R_1 . Due to its superior parameters, using S_4 but not S_3 in the network achieved an optimized design (see Table 1). First, the length (θ) of mx_4 was smaller than that of mx_3 , so the flow rate computed using S_4 was smaller than that using S_3 for an equal amount of mass exchange. Second, since both streams were external mass separating agents, higher purchasing costs were computed the higher the flow rate required. Finally, when counting the number of stages for each exchanger, the number of plates required in mx_3 using the adsorbent (S_3) was greater than the number of plates required in mx_4 using the stripping agent (S_4) to integrate the same mass load below the pinch. These results are comparable to those that had been previously obtained using the graphical approach, as described in Section 2 [10,20]. Fig. 10 depicts the mass exchanger units to be implemented in the process.

4. Conclusions

Matrix Laboratory (MATLAB) has a large number of applications, including the application of numerical algebraic equations, analyzing and visualizing data, plotting graphs, and algorithm development. The algorithmic approach presented

by this is a novel innovation. The MATLAB code presented in this paper was developed to run a graphical technique for the design of MENs, using a composition driving force (CDF) and validated through a real case study.

The algorithmic approach presented applies pinch analysis in its settings and may be considered an efficient tool to deal with more complex processes. The main advantage of such a model is that it eliminates human error during the design process. The model was applied to a practical case in which MENs had been designed graphically in a previous work in order to validate the developed algorithm and check its validity. This approach is based on segmenting rich streams and lean streams (process streams and external MSAs) by compositions. The targeted species from rich streams are then stripped off to be transferred to leaner streams, where any deficiencies are covered by external mass separating agents and any surpluses are passed to the next interval. The whole mass integration operation is controlled and regulated by the composition driving forces and guaranteed by pinch principles. The results obtained from this procedure conform to those previously obtained using the graphical method. This method is unique in the fact that it identifies and designs the best mass exchanger matches to enhance the performance of existing MENs or new ones with the maximum mass integration recovery, maximum usage of process lean streams, and minimum usage of external mass separating agents.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. MATLAB Code

Input Data

```

%Rich streams in kg/s
Rs1=500;      Rt1=50;   G1=0.2;
%lean streams in kgmole/s
m1=0.5; m2= 1; m3= 0.8; m4= 0.2;
eta1=200; eta2=100; eta3=50; eta4=50;
% lean streams compositions
xs1=200; xt1=900;      L1= 0.15;
xs2=300; xt2=1000;
xs3=10;  xt3=200;
xs4=20;  xt4=600;
% equivelant lean streams
Ss1=m1*(xs1+eta1);
St1=m1*(xt1+eta1);
Ss2=m2*(xs2+eta2);
St2=m2*(xt2+eta2);
Ss3=m3*(xs3+eta3);
St3=m3*(xt3+eta3);
Ss4=m4*(xs4+eta4);
St4=m4*(xt4+eta4);

%units in kg/s
clc;clear;close all
%Rich streams in kg/s
Rs1=500;      Rt1=50;   G1=0.2;
%lean streams in kgmole/s
m1=0.5; m2= 1; m3= 0.8; m4= 0.2;
eta1=200; eta2=100; eta3=50; eta4=50;
% lean streams compositions
xs1=200; xt1=900;      L1= 0.15;
xs2=300; xt2=1000;
xs3=10;  xt3=200;
xs4=20;  xt4=600;
% equivelantequivalent lean streams
Ss1=m1*(xs1+eta1);
St1=m1*(xt1+eta1);
Ss2=m2*(xs2+eta2);
St2=m2*(xt2+eta2);
Ss3=m3*(xs3+eta3);
St3=m3*(xt3+eta3);
Ss4=m4*(xs4+eta4);
St4=m4*(xt4+eta4);
% Pinch streams
Xeqvp=200;      Yp=200;
% minimum composition difference
m=[0.5 1 0.8 0.2 ];
eta=[200 100 50 50];
DCmin=-m.*eta;
hold on
% Rich streams lines
x=[Rs1,0];y=[0,Rs1];plot(x,y,'r-') % line1
x=[Rt1,0];y=[0,Rt1];plot(x,y,'r-') % line2

```

```

% Y pinch line
x=[Yp,0];y=[0,Yp];plot(x,y,'k-') % line1
% lean streams lines
y = ylim;
plot([Ss1 Ss1],[y(1) y(2)],'b-') % lean line 1
plot([St1 St1],[y(1) y(2)],'b-') % lean line 1
plot([Ss2 Ss2],[y(1) y(2)],'b-') % lean line 2
plot([St2 St2],[y(1) y(2)],'b-') % lean line 2
plot([Ss3 Ss3],[y(1) y(2)],'b-') % lean line 3
plot([St3 St3],[y(1) y(2)],'b-') % lean line 3
plot([Ss4 Ss4],[y(1) y(2)],'b-') % lean line 4
plot([St4 St4],[y(1) y(2)],'b-') % lean line 4
% Xeqv pinch line
plot([Xeqvp Xeqvp],[y(1) y(2)],'k-') % cold pinch
x = xlim;
plot([x(1) x(2)], [0 0], 'k-')
% Datum lines
plot([x(1) x(2)], [DCmin(1) DCmin(1)], 'k-')
plot([x(1) x(2)], [DCmin(2) DCmin(2)], 'k-')
plot([x(1) x(2)], [DCmin(3) DCmin(3)], 'k-')
plot([x(1) x(2)], [DCmin(4) DCmin(4)], 'k-')
xlabel('Xeqv')
ylabel('delta C')
title('CDF')
%%%%%%%%%% Above the pinch %%%%%%%%%%
%1
if Rt1<= Yp
    Rt1=Yp;
end
if Ss1<=Xeqvp
    Ss1=Xeqvp;
end
% 2
if Ss2<=Xeqvp
    Ss2=Xeqvp;
end
% 3
if Ss3<=Xeqvp
    Ss3=Xeqvp;
end

A=[1 1;1 0]; k=1;
Rich_streams=[Rs1 Rt1 Yp];
lean_streams=[Ss1 St1 Ss2 St2 Ss3 St3 Ss4 St4 Xeqvp];
for i=1:length(Rich_streams)
    for j=1:length(lean_streams)
        sol{i,j}=inv(A)*[Rich_streams(i);lean_streams(j)];
        % %% this part to remove solutions less than Tcp
        if sol{i,j}(2)>=Xeqvp||sol{i,j}(1)>=Yp
            sol2{k}=sol{i,j};
            k=k+1;
        end
    end
end
end
%%%% first exchanger %%%%%%%%%%
intersection1=sol{3,1}; %% changed from the results of sol
slope1=(L1/(m1*G1))-1;

```

```

length_of_arrow=y_lim;
thetal=atan(slope1);
x_max=intersection1(1)+length_of_arrow(2)*cos(thetal);
y_max=intersection1(2)+length_of_arrow(2)*sin(thetal);
x=[intersection1(1) x_max];
y=[intersection1(2) y_max];
h=line(x,y);
%%% the simple prof, we can get the form of the line passing through
two
%%% points (x1,y1) and (x2,y2) as following
%%%  $X(y_2-y_1) - Y(x_2-x_1) = x_1(y_2-y_1) - y_1(x_2-x_1)$ 
%%% to get the arrow interstions with :
new_Rich1=Rich_streams;
new_lean1=lean_streams;

Rich_A=[1 1;y_max-intersection1(2) intersection1(1)-x_max];
lean_A=[1 0;y_max-intersection1(2) intersection1(1)-x_max];
deltaC_A=[0 1;y_max-intersection1(2) intersection1(1)-x_max];
for i=1:length(new_Rich1)

intersections_Rich{i}=inv(Rich_A)*[new_Rich1(i);intersection1(1)*(y_max-
-intersection1(2))-intersection1(2)*(x_max-intersection1(1))];
end
for i=1:length(new_lean1)

intersections_lean{i}=inv(lean_A)*[new_lean1(i);intersection1(1)*(y_max-
-intersection1(2))-intersection1(2)*(x_max-intersection1(1))];
end
intersections_deltaC=inv(deltaC_A)*[DCmin(1);intersection1(1)*(y_max-
-intersection1(2))-intersection1(2)*(x_max-intersection1(1))];
%%% end point of the first exchanger %%%%
Endpoint1=intersections_Rich{1};
%%% drawing line from intersection 1 and end point1
x=[intersection1(1) Endpoint1(1)];
y=[intersection1(2) Endpoint1(2)];
delete(h)
plot (x,y)
leng1=((Endpoint1(1)-intersection1(1))^2+((Endpoint1(2)-
intersection1(2)))^2)^0.5;
Delta_M1=(leng1*L1*G1)/((L1-m1*G1)^2+(m1*G1)^2)^0.5;
%%%%%%%% second exchanger %%%%%%%%%%
intersection2=sol{3,3};
intersection2_2=sol{1,4};

slope_2=tan((intersection2_2(2)-intersection2(2))/(intersection2_2(1)-
intersection2(1)));
L2=(slope_2+1)*m2*G1;
x=[intersection2(1) intersection2_2(1) ];
y=[intersection2(2) intersection2_2(2)];
h2=line(x,y);

%%%%%%%%%% below the pinch %%%%%%%%%%

%Rich streams in kgmole/s
Rs1=500;      Rt1=50;  G1=0.2;
%lean streams in kgmole/s

```

```

m1=0.5; m2= 1; m3= 0.8; m4= 0.2;
eta1=200; eta2=100; eta3=50; eta4=50;
% lean streams compositions
xs1=200; xt1=900;      L1= 0.15;
xs2=300; xt2=1000;
xs3=10;  xt3=200;
xs4=20;  xt4=600;
% equivalent lean streams
Ss1=m1*(xs1+eta1);
St1=m1*(xt1+eta1);
Ss2=m2*(xs2+eta2);
St2=m2*(xt2+eta2);
Ss3=m3*(xs3+eta3);
St3=m3*(xt3+eta3);
Ss4=m4*(xs4+eta4);
St4=m4*(xt4+eta4);
% Pinch streams
Xeqvp=200;      Yp=200;
% minimum composition difference
m=[0.5 1 0.8 0.2 ];
eta=[200 100 50 50];
DCmin=-m.*eta;

%%%% 1
if Rs1>=Yp
    Rs1=Yp;
end
if St1>=Xeqvp
    St1=Xeqvp;
end
% 2
if St2>=Xeqvp
    St2=Xeqvp;
end
% 3
if St3>=Xeqvp
    St3=Xeqvp;
end
% 4
if St4>=Xeqvp
    St4=Xeqvp;
end

%%%% solving to get all intersections
A=[1 1;1 0]; k=1;
Rich_streams=[Rs1 Rt1 Yp];
lean_streams=[Ss1 St1 Ss2 St2 Ss3 St3 Ss4 St4 Xeqvp];
for i=1:length(Rich_streams)
    for j=1:length(lean_streams)
        sol{i,j}=inv(A)*[Rich_streams(i);lean_streams(j)];
        % this part to remove solutions less than Tc
        if sol{i,j}(2)<=Xeqvp&&sol{i,j}(1)<=Yp
            sol3{k}=sol{i,j};
            k=k+1;
        end
    end
end
end

```

```

end

%%%% first exchanger %%%%%%%%%
intersection1=sol3{3};
intersection2=sol3{12};
%plot(intersection2(1),intersection2(2),'dk')
slope_3=tan((intersection2(2)-intersection1(2))/(intersection2(1)-
intersection1(1)));
L3=(slope_3+1)*m3*G1;

x=[intersection1(1) intersection2(1)];
y=[intersection1(2) intersection2(2)];
h3= line (x,y);
leng3=((intersection2(1)-intersection1(1))^2+((intersection2(2)-
intersection1(2)))^2)^0.5;
Delta_M3=(leng3*L3*G1)/((L3-m3*G1)^2+(m3*G1)^2)^0.5;
%%%% second exchanger %%%
intersection1=sol3{7};
intersection2=sol3{14};
%plot(intersection2(1),intersection2(2),'dk')
slope_4=tan((intersection2(2)-intersection1(2))/(intersection2(1)-
intersection1(1)));
L4=(slope_4+1)*m4*G1;
x=[intersection1(1) intersection2(1)];
y=[intersection1(2) intersection2(2)];
h4= line (x,y);
leng4=((intersection2(1)-intersection1(1))^2+((intersection2(2)-
intersection1(2)))^2)^0.5;
Delta_M4=(leng4*L4*G1)/((L4-
m4*G1)^2+(m4*G1)^2)^0.5;

```

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