Synthesis of Mass Exchange Networks: A Graphical Approach.

A mass exchanger is any direct contact mass transfer unit that employs a mass separating agent MSA (or a lean stream) to selectively remove certain components from a rich stream. The stream from which the targeted components are removed is designated as rich stream while the stream to which the targeted components are transferred is referred as the lean stream (or MSA). The MSA should be partially or completely immiscible in the rich stream e.g. absorption, stripping, ion exchange, solvent extraction and leaching.

Multiple mass exchange units are used in process industries. Therefore, their selection, design and operation must be co-ordinated and integrated. In this chapter systematic approach to the synthesis of networks involving multiple mass exchangers is discussed.

Design of Individual Mass Exchangers

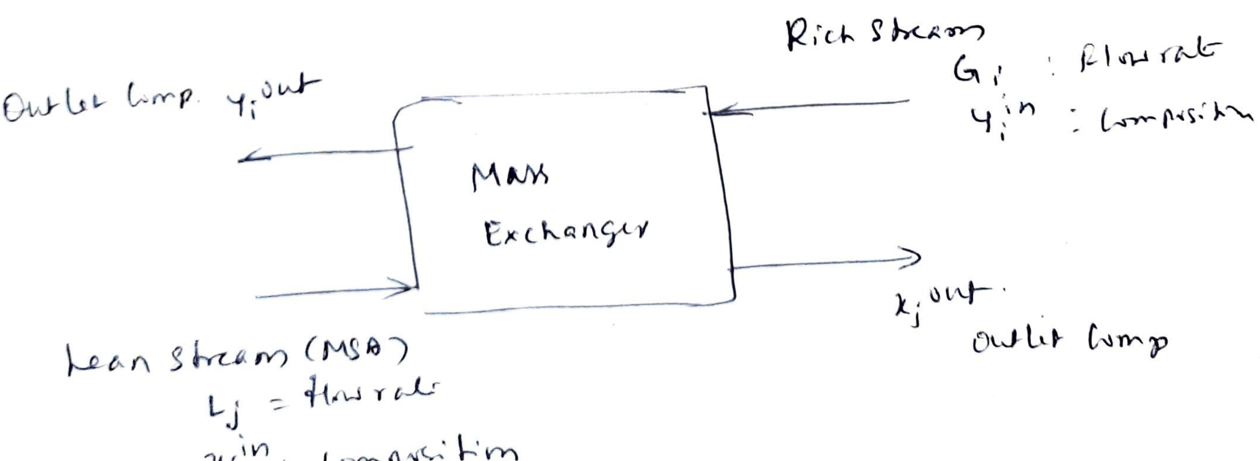


Fig. 1 A Generic Mass Exchanger

Consider the mass exchanger shown in Fig. 1.

A certain component is transferred from rich stream i, to the lean stream, j. The rich stream has a flow rate, G_i, an inlet composition y_i^{in}, and an outlet composition, y_i^{out}. The lean-stream has a flow rate, L_j, an inlet composition, x_j^{in}, and an outlet composition, x_j^{out}. Two important ~~functions~~ aspects govern the performance of mass exchanger: Equilibrium function and material balance.

Equilibrium refers to the state at which there is no net interphase transfer of the targeted species (solute). This situation corresponds to the state at which both phases have the same value of chemical potential for the solute. Mathematically, the composition of the solute in the rich phase, y_i, can be related to its composition in the lean phase, x_j, via an equilibrium distribution function f_j^*

$$y_i = f_j^* (x_j^*) \qquad (1)$$

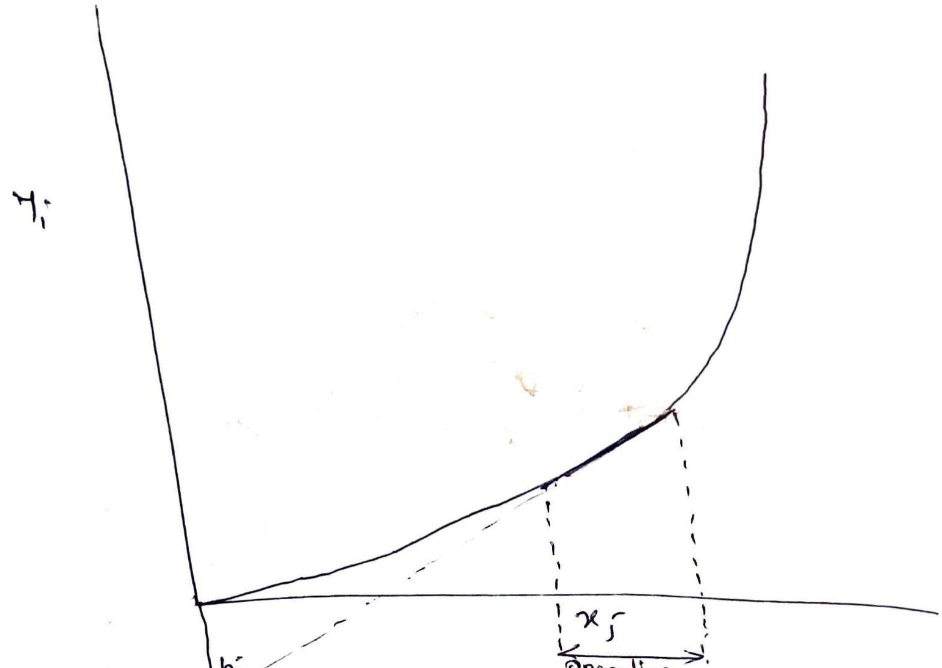


Fig. 2. Linearized segment of Equilibrium Function.

Fig. 2. is schematic representation of an equilibrium function. in many cases, the equilibrium function can be linearized over a specific range of operation. As shown in fig. 2. the linearized form has a slope m_j and an intercept b_j.

i.e

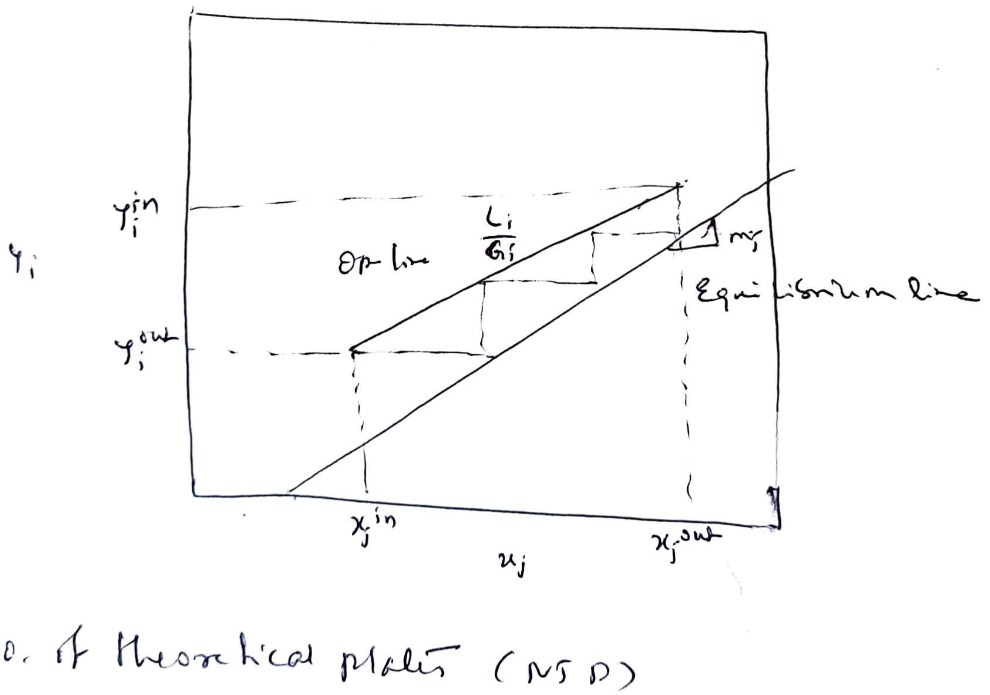
$$y_i = m_j x_j^* + b_j \qquad (2)$$

Material balance of solute

Solute lost from rich stream = Solute gained by lean stream

$$G_i (y_i^{in} - y_i^{out}) = L_j (x_j^{out} - x_j^{in})$$

This is Eqn of operating line



No. of theoretical plates (NTP)

$$NTP = \frac{\ln\left[\left(1 - \left(m_j G_i / L_j\right)\right)\left(y_i^{in} - m_j x_j^{in} - b_j / y_i^{out} - m_j x_j^{in} - b_j\right) + \left(m_j G_i / L_j\right)\right]}{\ln\left(L_j / m_j G_i\right)}$$

No of actual plates (NAP)

$$NAP = \frac{NTP}{\eta_o}$$

for packed units, spray exchangers

$$H = HTU_y \, NTU_y$$

$$= HTU_x \, NTU_x .$$

where HTU_x, HTU_y are the overall height of transfer units based on the rich and lean phases.

$$NTU_y = \frac{y_i^{in} - y_i^{out}}{(y_i - y_i^*)\,\text{log mean}}$$

when $$(y_i - y_i^*)\,\text{log mean} = \frac{(y_i^{in} - m_j x_j^{out} - b_j) - (y_i^{out} - m_j x_j^{in} - b_j)}{\ln\left[(y_i^{in} - m_j x_j^{out} - b_j)/(y_i^{out} - m_j x_j^{in} - b_j)\right]}$$

and $$NTU_x = \frac{x_j^{in} - x_j^{out}}{(x_j - x_j^*)\,\text{log mean}}$$

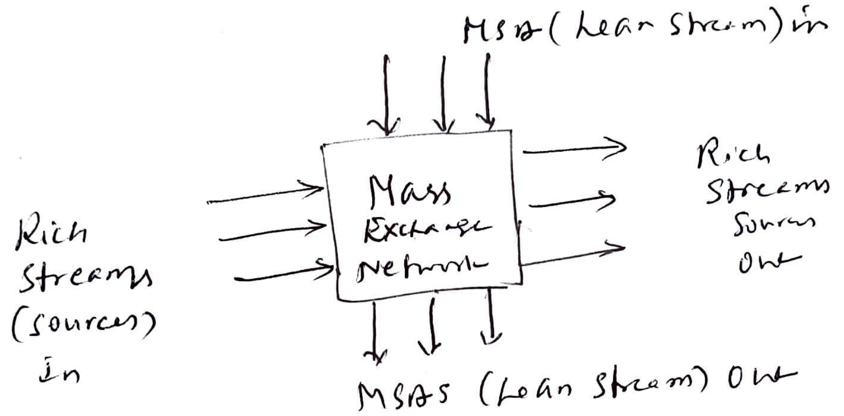
where

$$(x_j - x_j^*)\,\text{log mean} = \frac{\left[x_j^{out} - (y_i^{in} - b_j/m_j)\right] - \left[x_j^{out} - b_j/m_j\right]}{\ln\left\{\left[x_j^{out} - (y_i^{in} - b_j/m_j)\right]/\left[x_j^{in} - (y_i^{out} - b_j/m_j)\right]\right\}}$$

Problem Statement for Synthesis of mass Exchange Networks

In many processing facilities, mass exchangers are used to separate targeting species from a number of rich streams. More than one mass exchange technology and more than one MSA may be considered. In such cases it is necessary to integrate and design of multiple mass exchangers.

Identification of optimum network of mass exchangers is synthesis of mass exchange network.



The rich streams leaving MEN are either allocated to process sinks (equipment) or assigned to terminal streams (eg. products, waste).

The target composition of each MSA is an upper bound on the actual outlet composition of the MSA

The target composition is selected based on a number of factors

Physical (es. saturation compositions, solubility limits, precipitation conditions)

Safety (flammability / explosion)

Health (toxicity)

Environmental (emission regulations)

Economic (minimize cost)

Technical (Thermodynamic constraints & min. driving force)

The MEN Synthesis task involves ~~answer~~ the following design questions

1. Which mass exchange technologies should be utilized (e.g. solvent extraction, adsorption)

2. Which MSAs should be selected? (e.g. solvent, adsorbent

3. What is the optimal flow rate of each MSA?

4. How should these MSAs ~~matched~~ matched with the rich stream

5. What is the optimal system configuration (how should these mass exchangers be arranged?). Is there any stream splitting and mixing?

Mass Exchange Pinch Diagrams.

The mass exchange pinch analysis provides a holistic and systematic approach to synthesizing MENS. It also enables the identification of rigorous targets such as minimum cost of MSAs. The first step in the analysis is to develop an integrated view of all the separation tasks for the rich streams. This can be acheived by developing a composite representation of mass exchanged from all the rich streams. Mass of the targeted species removed from the i^{th} rich stream is given by

$$MR_i = G_i (y_i^s - y_i^t) \qquad i = 1, 2, \ldots, N_R$$

By plotting mass exchanged versus composition, each rich stream is represented as an arrow which tail corresponds to its supply composition and its head to its target composition. The slope of each arrow is equal to the stream flow rate. The vertical distance between the tail and head of each arrow represents the mass of targeted species that is lost by the rich streams, Any stream can be moved up or down while preserving the same supply and target compositions. A stream cannot be moved left or right, otherwise stream compositions will be altered. A convenient way of vertically placing each arrow is to rank the rich streams in ascending order of their targeted composition then we stack the rich streams on top of one another, starting with the rich stream having the lowest target composition. Once the first rich stream is represented, ~~as an arrow extending between its supply and target compositions~~ we draw a horizontal line passing thro' the arrow tail of the stream. Next, the second rich stream is represented as an arrow extending between its supply and target compositions and having a vertical distance equal to the mass of the targeted species to be removed from this stream. The arrow head of the second rich stream is placed on the horizontal line passing thro' the arrow tail of the first rich stream. The procedure is continued for all the rich streams (Fig.1.)

move ↑↓ ok ✓

⇄ ✗

s - supply
t - target

Slope = Stream flowrate

vertical distance MR_1 = mass of targeted sp. exch.

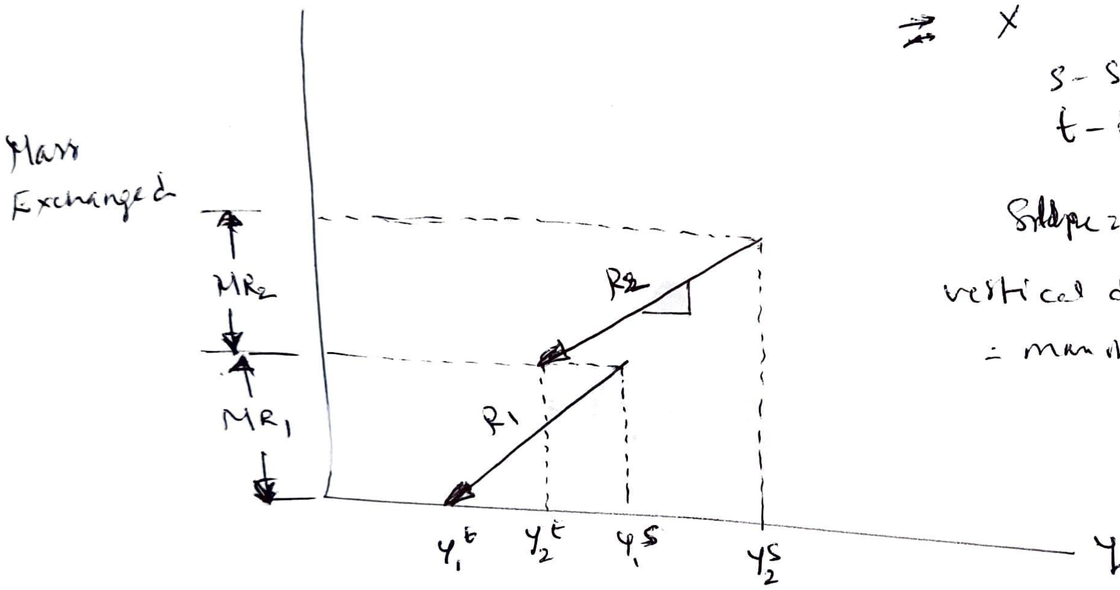


Fig.1. Representation of mass exchanged by two rich streams

After ~~the~~ all the rich streams have been represented, it is necessary to develop a combined representation of the rich streams that allows us to observe the separation tasks of all rich streams as a function of composition.

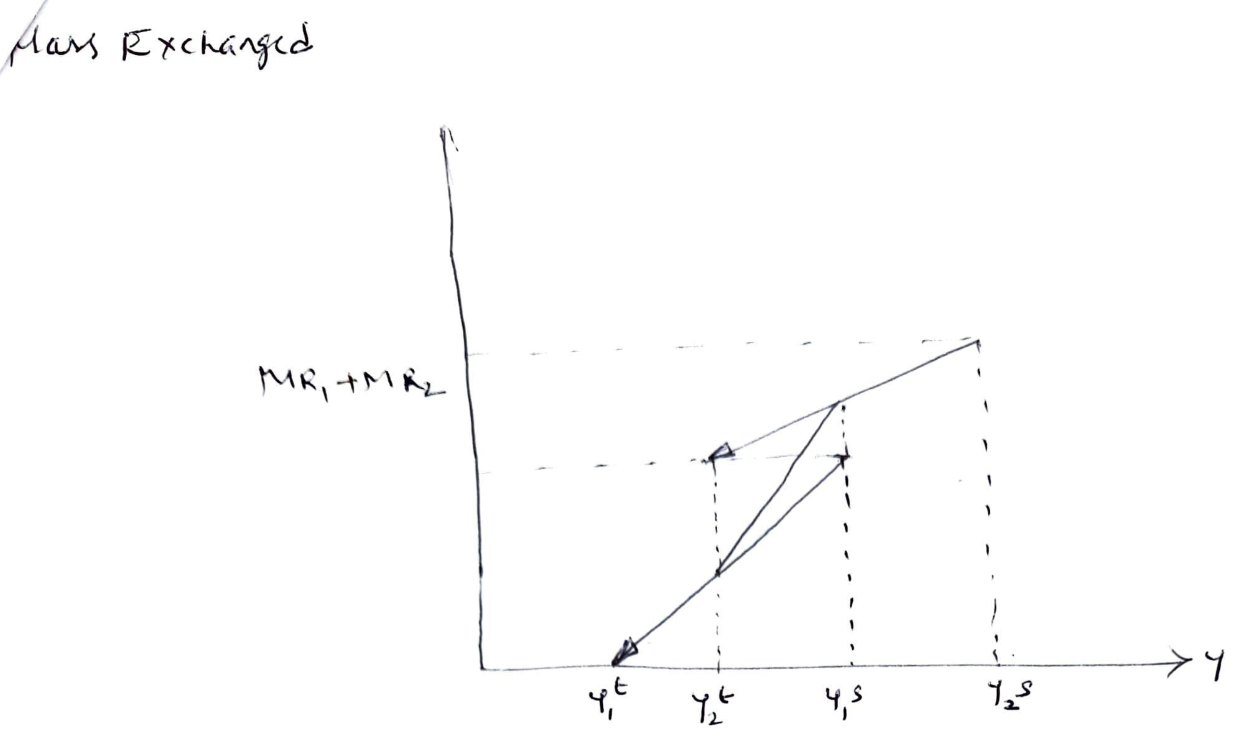


Fig 2. Constructing rich composite stream using superposition

A rich composite stream can be constructed using diagonal rule for superposition to add up mass in the overlapped regions of streams, (fig 2). In the region between y_1^t and y_2^t there is only R_1, Therefore the composite representation is exactly the same as R_1. Similarly in the region between y_1^s and y_2^s there is only R_2 and hence the composite representation is exactly the same as R_2. in the overlapping region of the two streams (between y_2^t and y_1^s), the composite representation of the two streams is the diagonal (hence the name diagonal rule). By connecting these three linear segments, we now have a rich composite stream which represents the cumulative mass of the targeted species removed from all the rich streams.

Lean Streams.

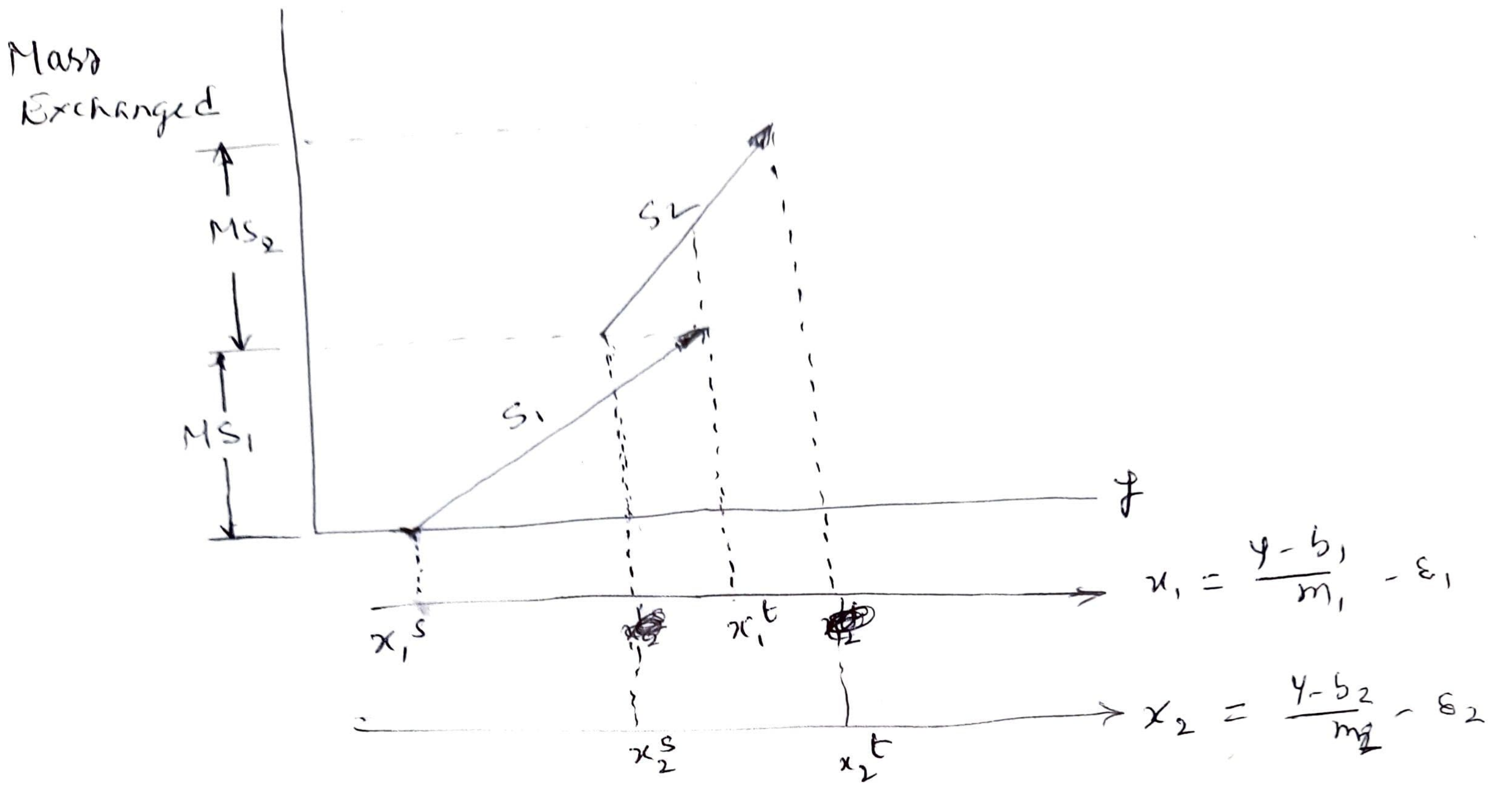


Fig. 3. Representation of mass exchanged by two process MSAs

Each process MSA is represented as an arrow extending between supply and target compositions (Fig. 3). The vertical distance between the arrow head and tail is given by

Mass of the solute that can be gained by the jth process MSA

$$MS_j = L_j^c (x_j^t - x_j^s)$$

Any stream can be moved up or down on the diagram. Arrows are placed on top of one another starting with the MSA having the lowest supply composition. (Fig. 3).

A lean composite stream representing the cumulative mass of the targeted species gained by all the MSA's is obtained by using the diagonal rule for superposition

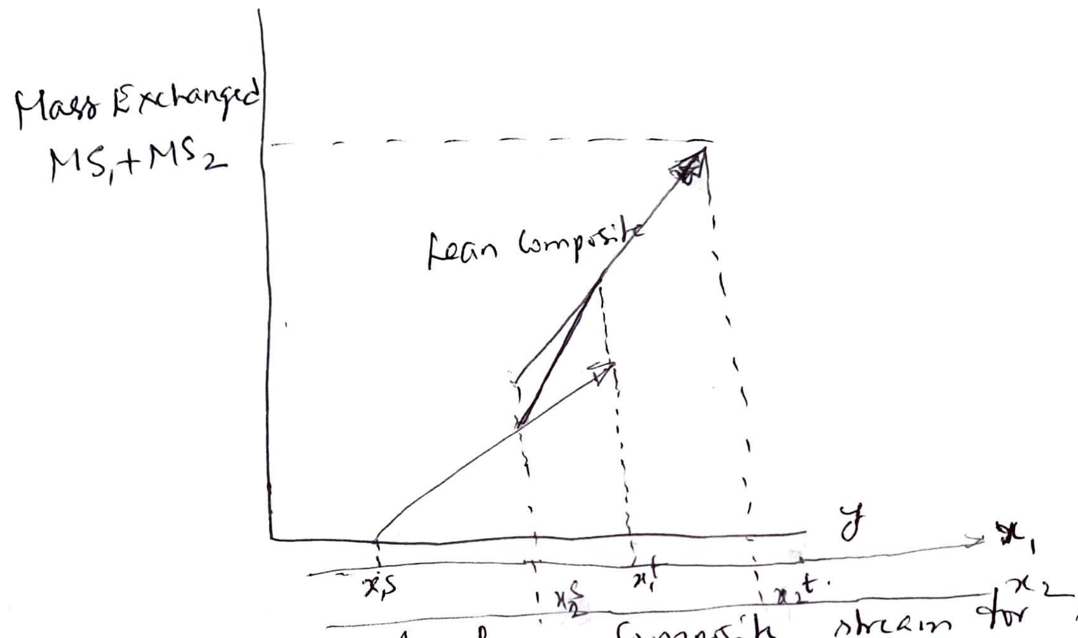


Fig. 4. Construction of lean composite stream for superposition.

Next both composite streams are plotted on the same diagram (Fig. 5)

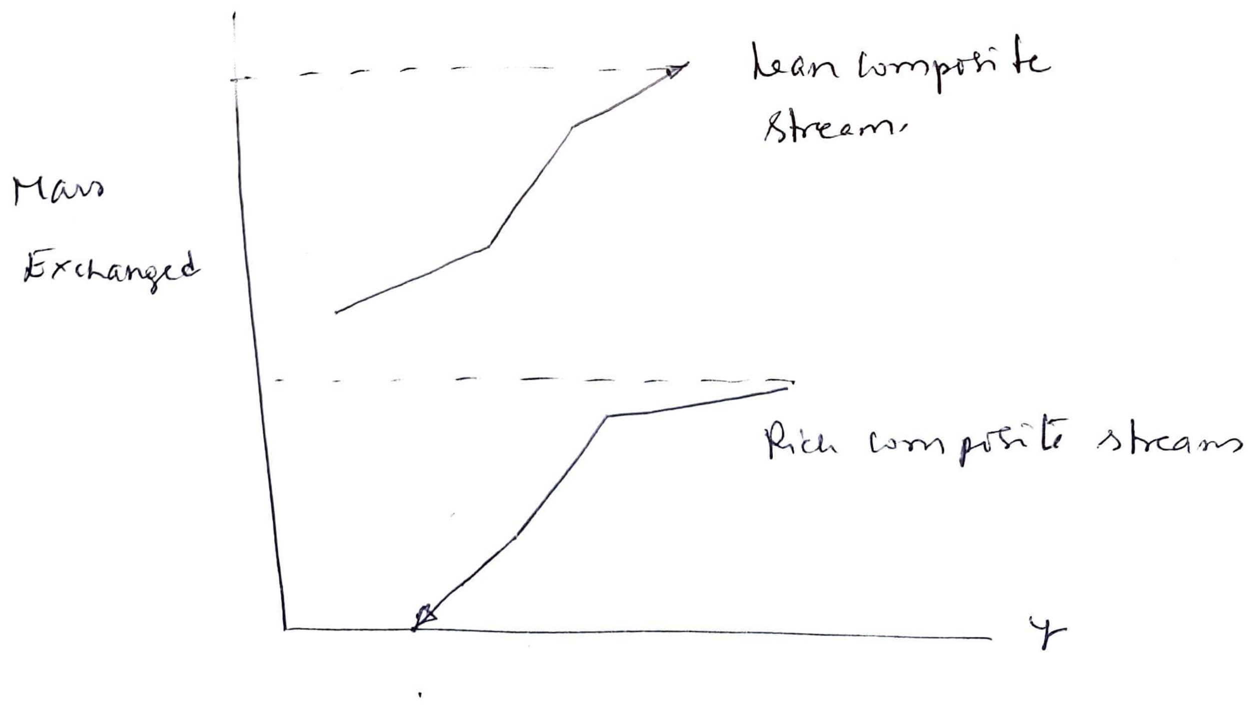


Fig. 5. No integration between rich and process MSAs

The lean composite stream can be moved up and down which implies different mass exchange decisions. For example; if we move the lean composite stream upwards in a way that leaves no horizontal overlap with the rich composite stream ~~and the process MSAs as~~ seen in Fig 5, then there is no integrated mass exchange between the rich composite stream and the process MSAs. When the lean composite stream is moved downwards ~~such~~ ~~that~~ so as to provide some horizontal overlap, some integrated mass exchange can be achieved (Fig 6). The ~~remaining~~ remaining load of the rich composite stream has to be removed by the external MSAs. However, if the lean composite stream is moved downwards so that the portion of the lean is placed to the right of the rich composite stream, thereby creating infeasibility (Fig 7). Therefore, the optimal situation is constructed when the lean composite stream is slid vertically until it touches the rich composite stream while lying completely to the left of the rich composite stream at any horizontal level. The point where the two composite streams touch is called the "mass exchange pinch point", hence the name pinch diagram (Fig. 8)

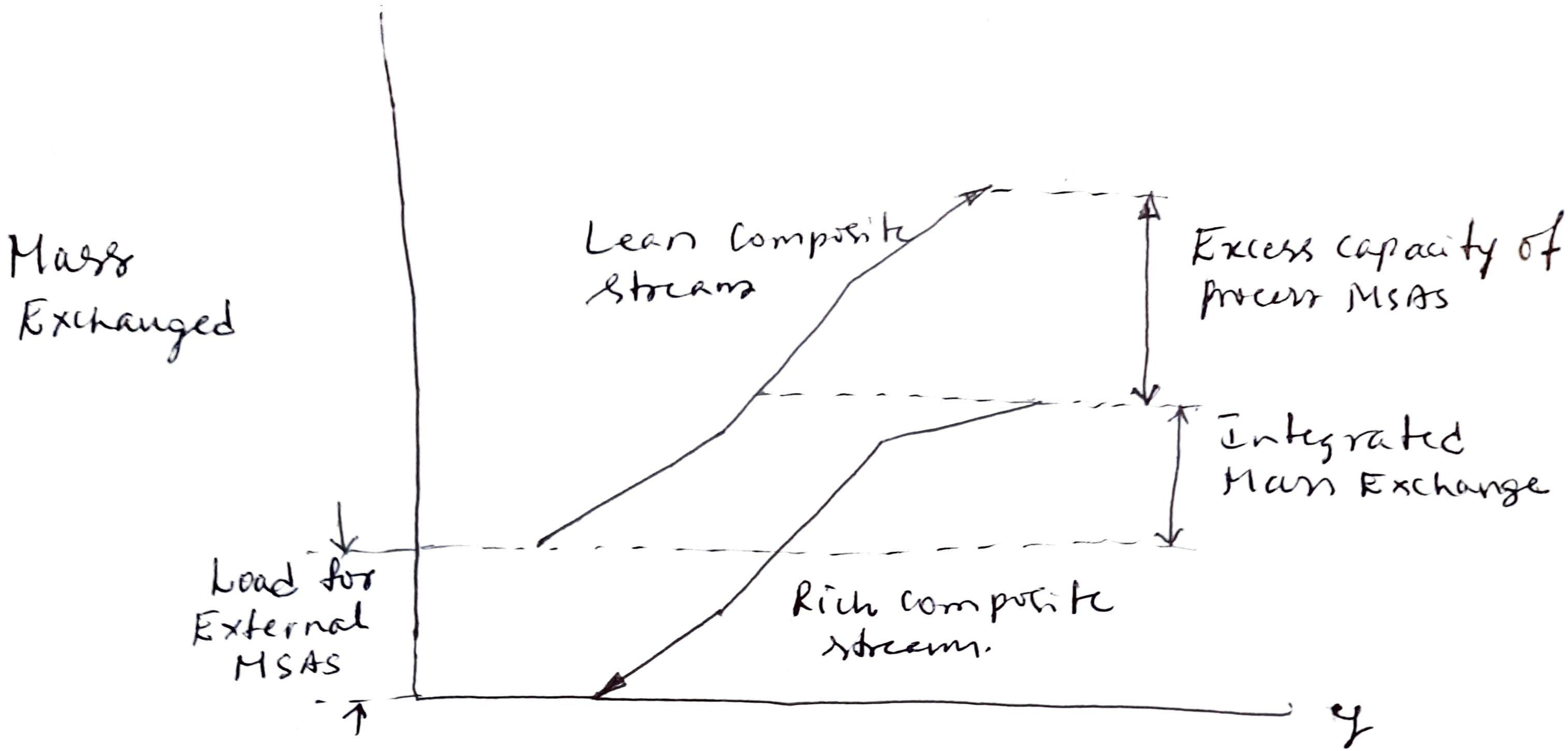


Fig 6. Partial Integration of Rich & Lean streams (passing Mass thro' pinch)

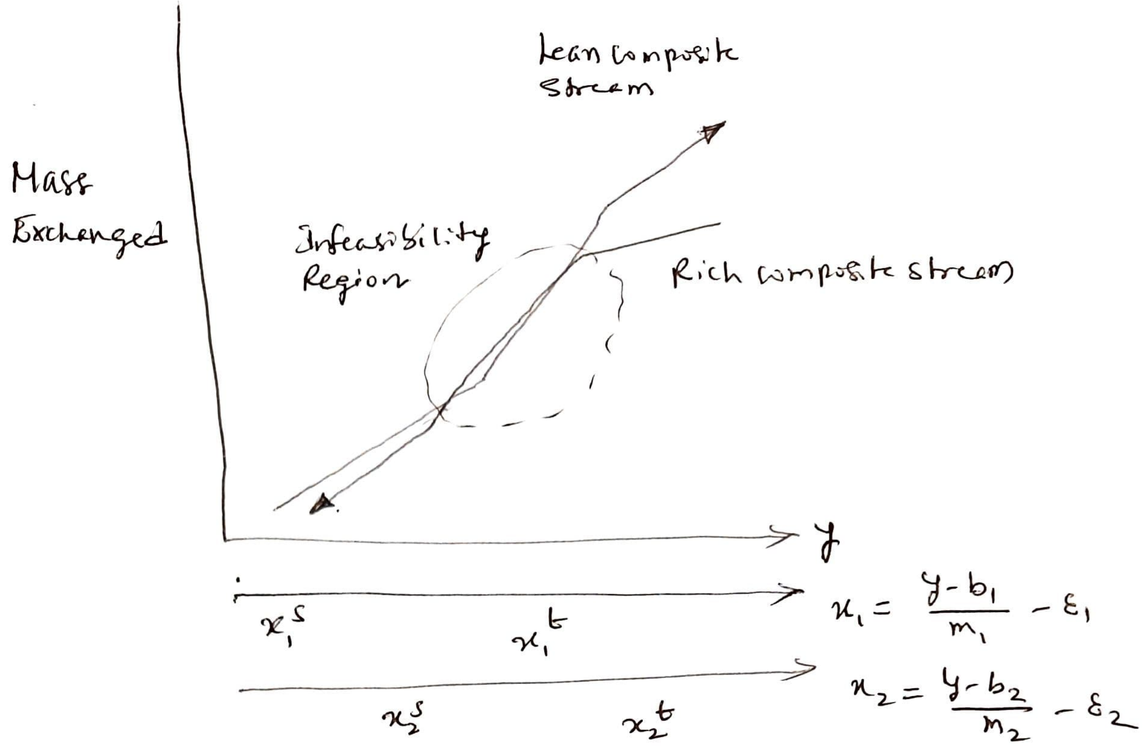


Fig 7. Causing infeasibility by placing lean to the right of the rich

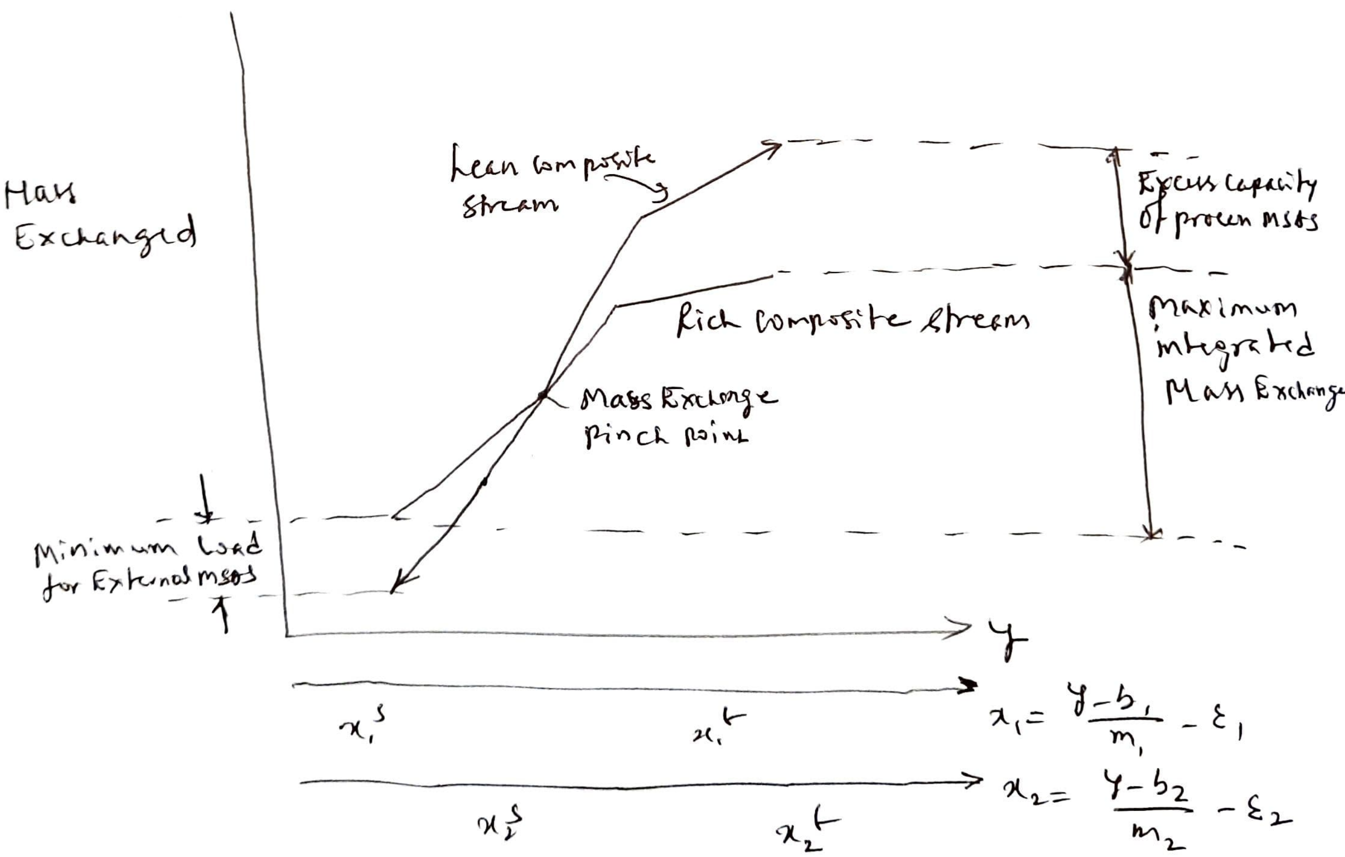


Fig 8. The mass Exchange pinch diagram