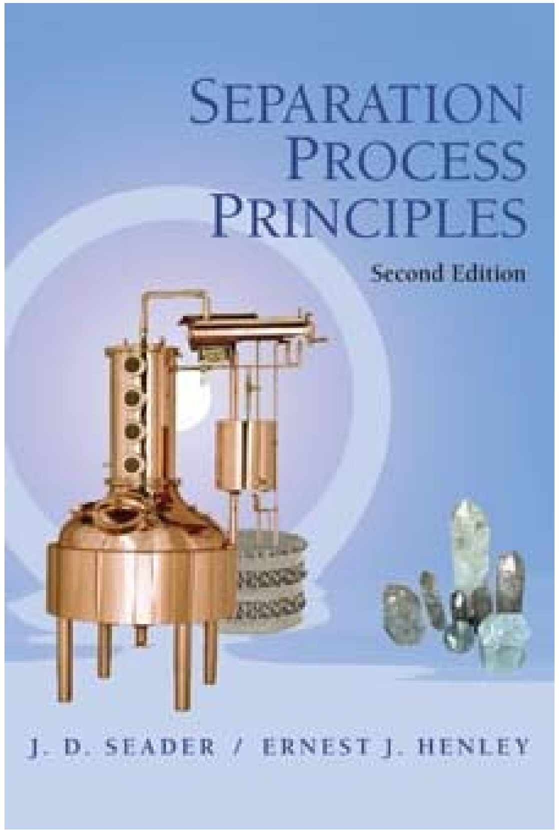
Mass Transfer II (502-315)

Mass Transfer Operations

Welcome!!

(to a new, useful, and exciting course)



Today's Lecture: Introduction to Separation Processes (Mass Transfer II)

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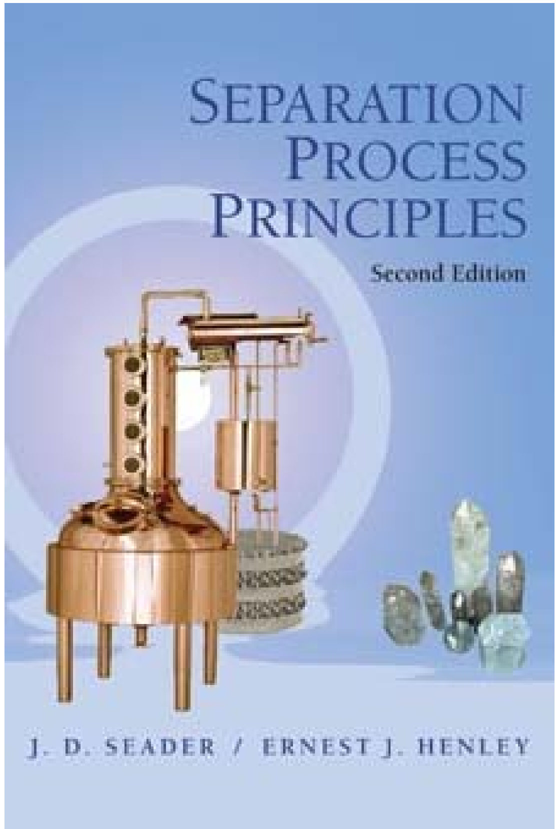
Office Hours: Open door policy when I am there, I am usually available. To guarantee availability, make an appointment

Textbook:
Separation Process Principles
Seader and Henley

Homework Assigned on Sundays/Due on next Sunday



SEPARATION PROCESS PRINCIPLES
Second Edition
J. D. SEADER / ERNEST J. HENLEY

What is this course about?

- Mass Transfer Operations: it deals with **“unit operations”** involving **“mass transfer” (a microscopic process in a macroscopic scale)**

- Within the context of this course, mass transfer is defined as the transportation of one (or more) component from one phase to another

- Motivation: in many industrial processes we use mass transfer to achieve **separation** (enrichment or removal) of a substance from a mixture

- Emphasis is placed on separation processes that involve equilibrium between the phases

- Unit operations are concerned with the analysis and design of equipment or processes.

Mass transfer operations are concerned with the analysis and design of equipment (single unit) and processes used in equilibrium-staged separations.

Why is this course useful to us?

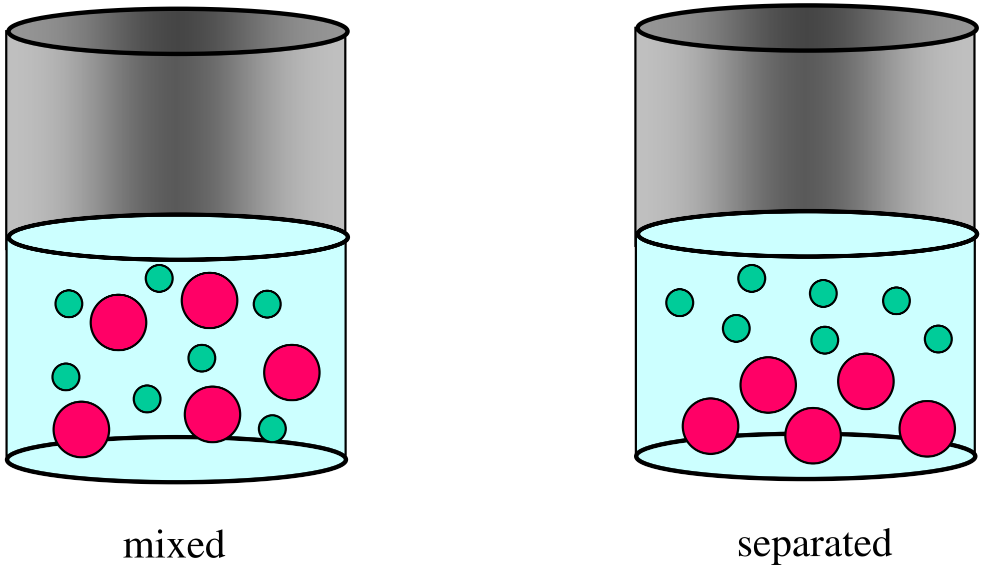
- Mass transfer operations is largely the responsibility of chemical engineers
- Chemical plants usually have from 50 to 90% of their capital invested in separation equipment
- There is virtually no industrial process that does not involve purification of raw materials or final separation of products
- ……..

Approximately three quarters of Chem. Eng. Graduates will find employment in industries where mass transfer operations play a critical role.

Introduction to Separations

The goal of a separations process is to purify solutions.

To do this we must cause differential transport of species or conversion of species so that the purer mixtures can be collected. Most separations processes involve differential transport.



Historical Examples:

Extract perfume from flowers
Evaporate seawater to get salt
Distill liquors
Purification of drugs
Kidney of human beings is like membrane
Refining of crude oil
Purification of organics

However, mixing is inherent in nature: The increase in entropy associated with the randomness of a mixture lowers the Gibbs free energy.

Therefore, to “unmix” a solution we must overcome the entropic driving force to mix.

Why Separate?

There are many reasons for wanting pure substances. Some of these reasons include:

- Need for pure material in engineering application (semiconductors)
- Need for pure material in chemicals production (reactors)
- Preparation of raw materials into their components
- Need to remove toxins or inactive components from solution (drugs)
- Need for ultrapure samples for testing
- Need to purify water for drinking use

→

- Enrichment
- Concentration
- Purification
- Refining
- Isolation

Based on these motivations for separations, we can divide separations up into three main areas:

Analytical Separations

- small scale
- quantitative analysis

Example: Chromatography

Preparative Separations

- small scale
- materials for R&D

Example: Centrifugation

CHEMISTS

Industrial Separations

- large scale
- economical

ENGINEERS

Example: Distillation

The list of different existing separations methods is limitless. Therefore we will emphasize the fundamentals of separations.

Note: 50 to 90 percent of capital investment in chemical plant is for separations equipment.

Background Material for Separations

The fundamentals that we will apply to study separations in this course involve:

- Materials and energy balances: conservation of energy and matter
- Thermodynamics: phase equilibrium and solution thermodynamics (Chapter 2)
- Transport phenomena (Chapter 3)
- Chemical reaction kinetics: rate of conversion of one species to another (not emphasized)

For the most part our analysis of various separations processes, we will focus on using phase equilibrium and materials and energy balances.

To study the rate of separation processes, we will focus on using Transport phenomena.

Basic Description of Operations

Separations processes can be run in various modes of operation:

- Batchwise: no flows
- Continuous: continuous flows in and out of separators
- Semicontinuous: pauses in flows.

Operations are classified as key operations and auxiliary operations

- Key Operation: involves reaction or separations
  - Examples: distillation, leaching, reactor
- Auxiliary Operation: involves no change in chemical composition
  - Examples: pumps, heaters, compressors

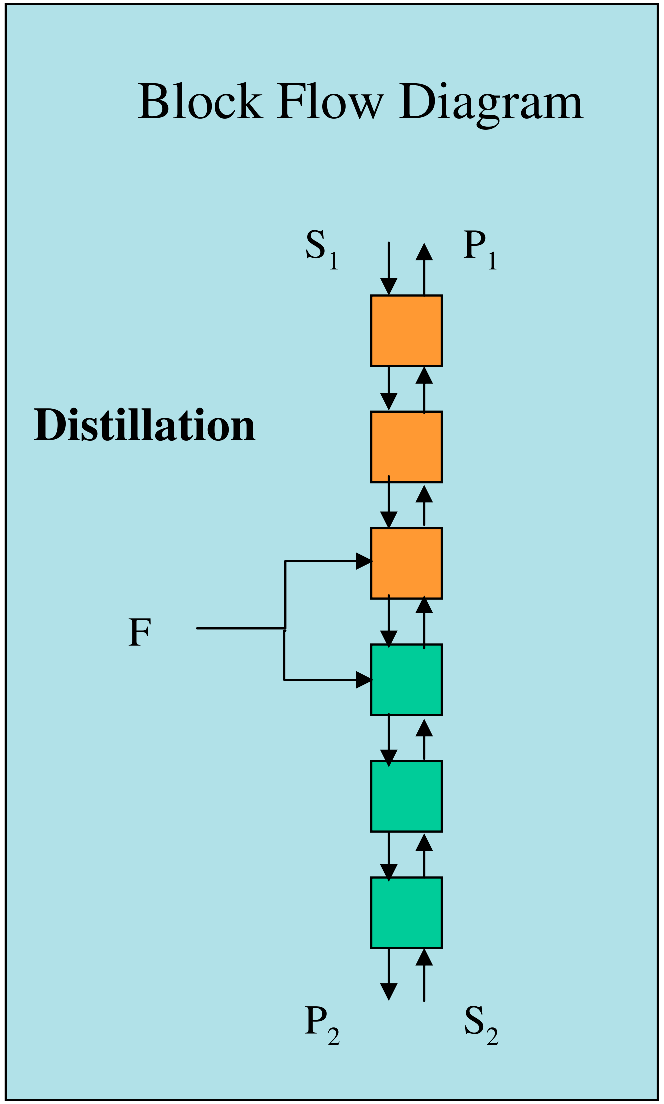
Block Flow Diagrams indicate:

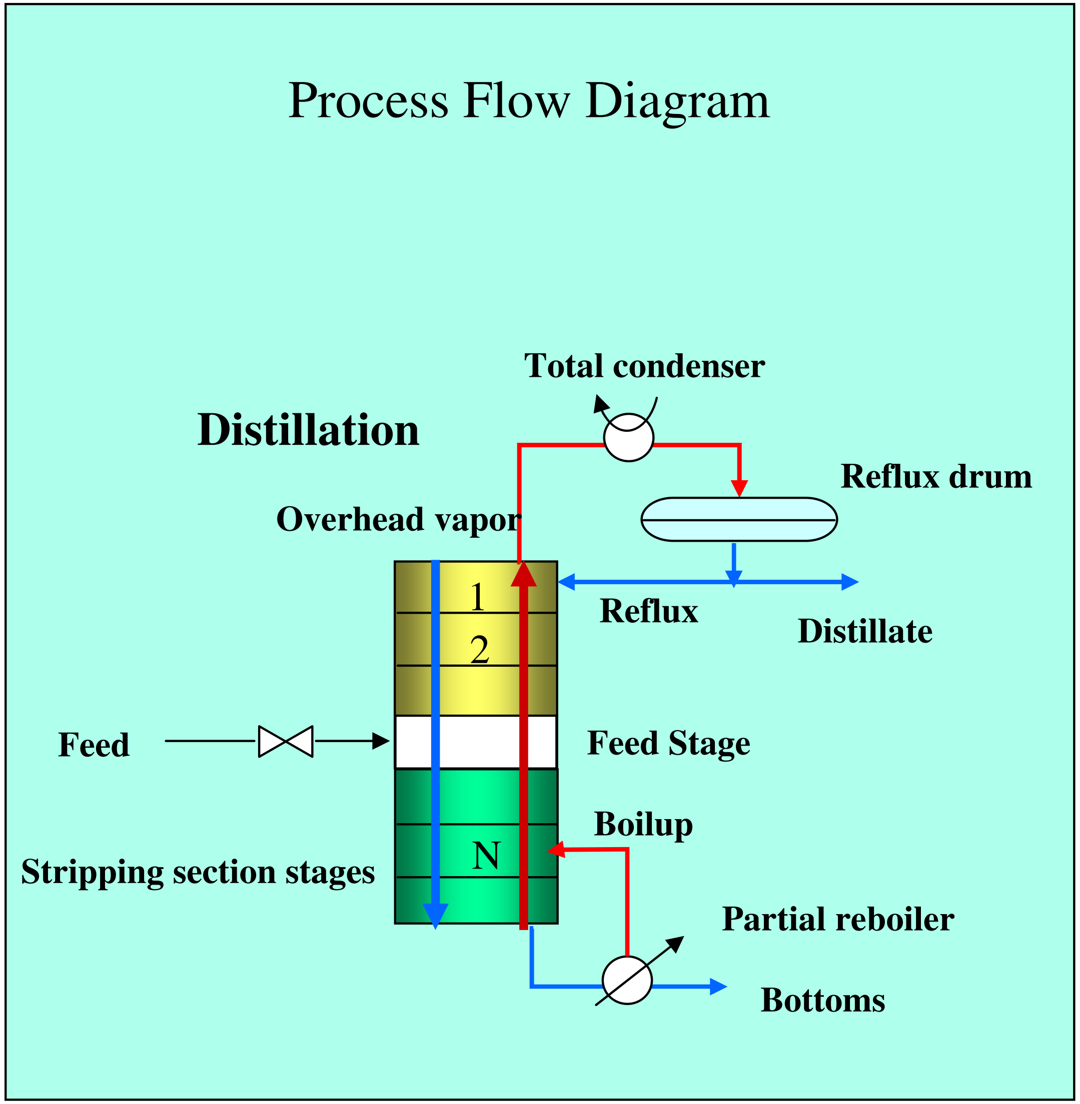
- Key Operations by rectangles and
- Flows and Streams by lines

Process Flow Diagrams indicates processes by:

- Realistic symbols of process equipment
- Including auxiliary operations

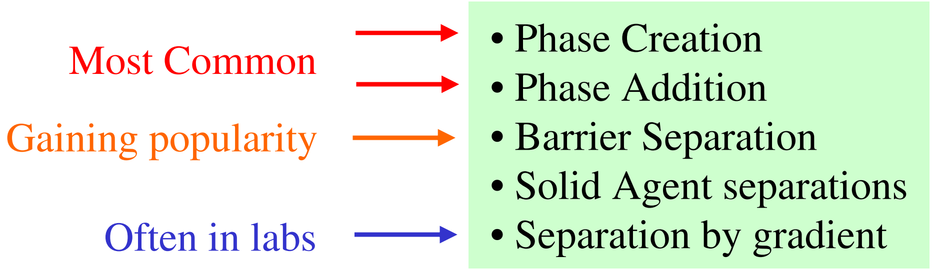
Basic Description of Operations





Main Separations Techniques

- Phase Creation: Use energy separating agent ESA (heat or depressurize)
- Phase Addition: Use mass separating agent MSA (add solvent or absorber)
- Barrier Separation: Use membrane (semipermeable membrane)
- Solid Agent separations: Use particles (reaction, absorbent film, direct absorption, chromatography)
- Separation by gradient: Use electric field, magnetic field, gravity (Hall effect, electrophoresis, mass spec)



- Phase Creation
- Phase Addition
- Barrier Separation
- Solid Agent separations
- Separation by gradient

All five techniques rely on the ability to enhance the rate of mass transfer of certain species relative to others to effect a spatial separation of components.

Thus, all separations processes must introduce a thermodynamic driving force
to overcome the decrease in the entropy of the system as the components are separated.

Unit Operations: Introduction

What is chemical engineering? Chemical Engineering is a group of industrial processes in which row materials are changed or separated into useful products

Historical development: As the **Industrial Revolution** steamed along certain basic chemicals quickly became necessary to sustain growth

- *Example*: Sulfuric acid was first among these "industrial chemicals".

Chemistry:

- to create a new substance
- to study its properties
- to investigate **all** possible pathways from one substance to another

Chemical Engineering:

- to design the most optimal technology for production of a specified substance from row materials
- to develop and discover new technological applications for materials

Process flowsheet: Example 1

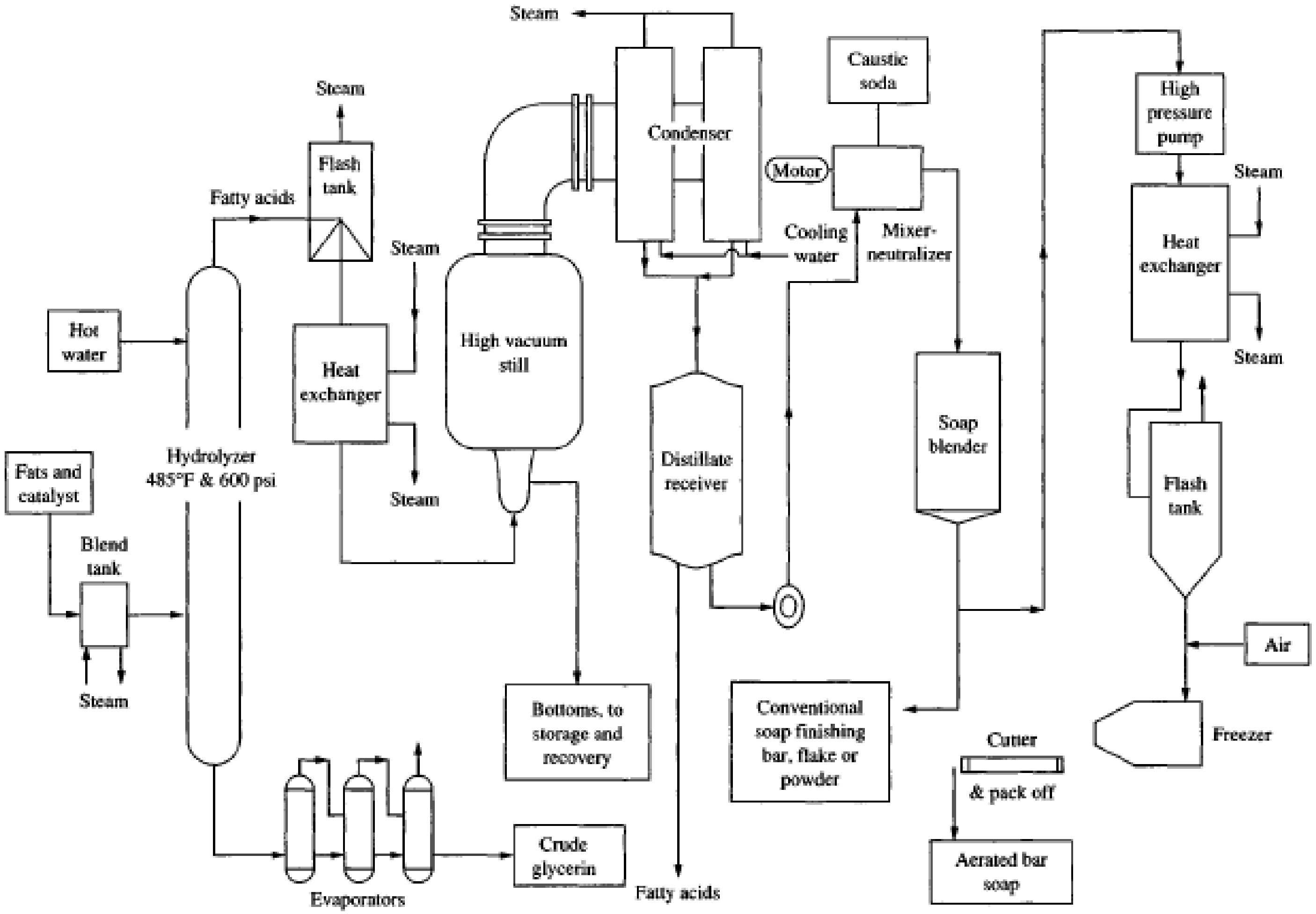


Figure 5.1 Continuous process for fatty acids and soaps.

Process flowsheet: Example 2

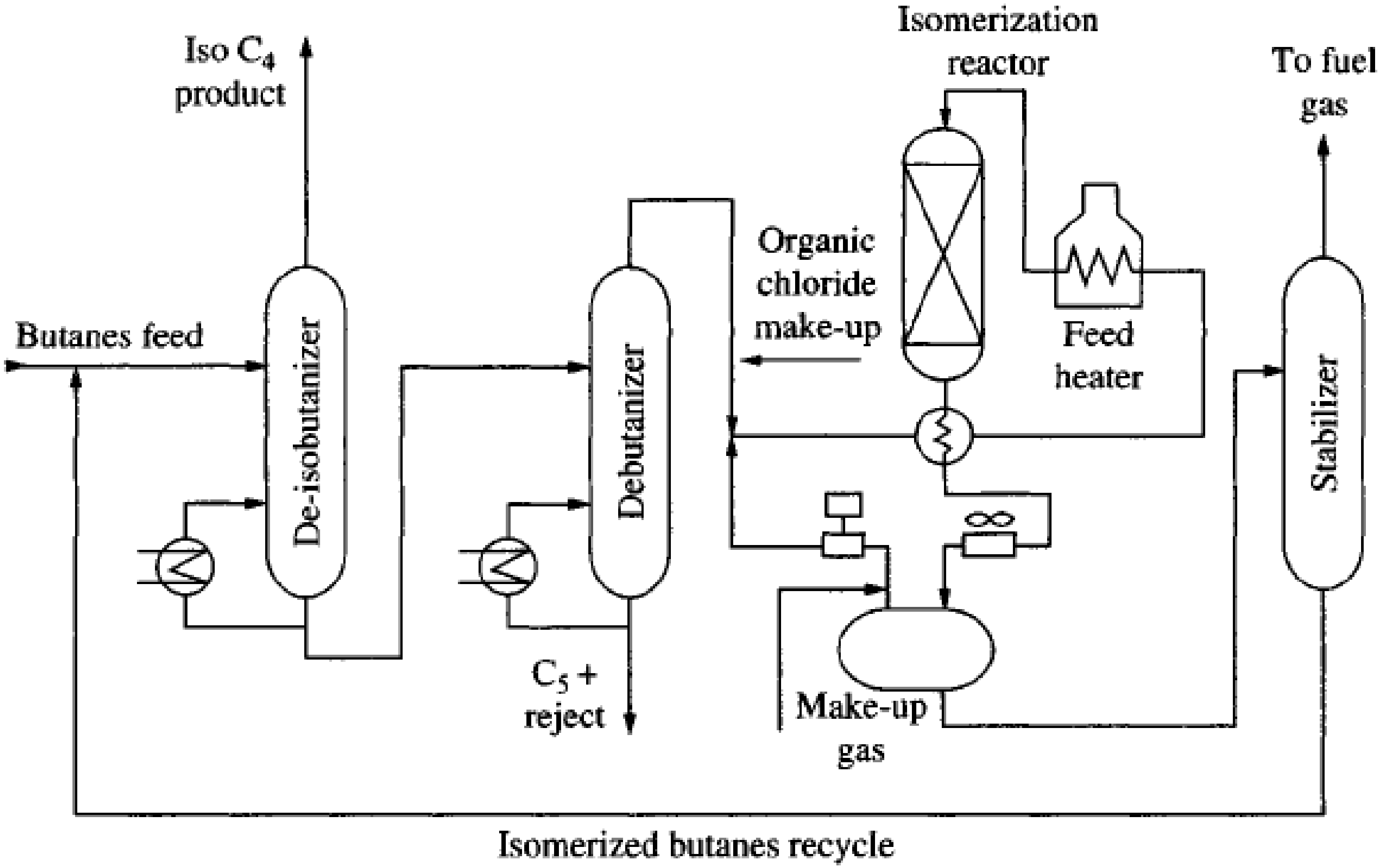


Figure 13.12 A butane isomerization unit

Comparison of two processes

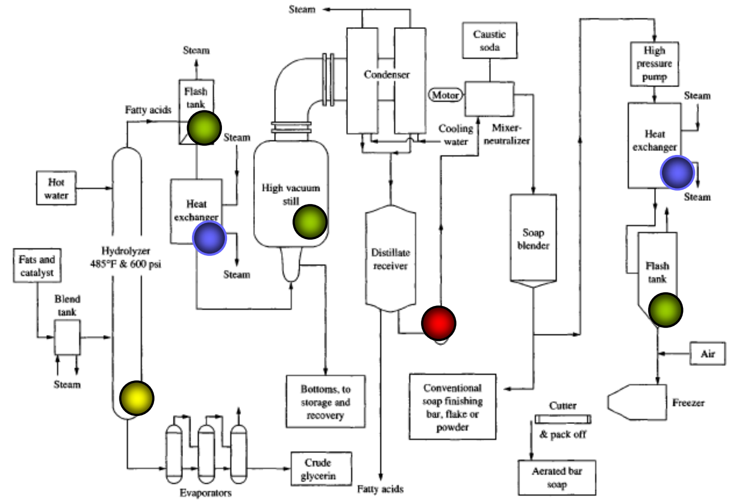


Figure 5.1 Continuous process for fatty acids and soaps.

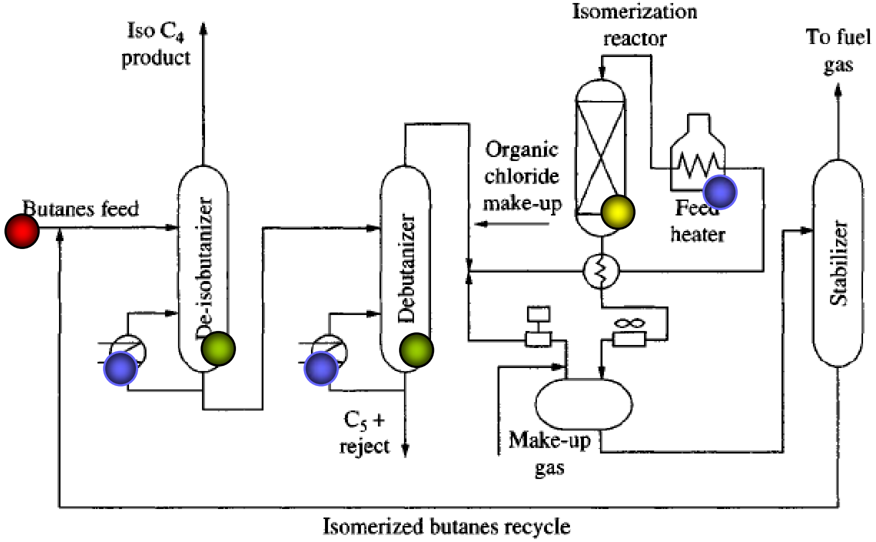


Figure 13.12 A butane isomerization unit

Units:

- Heaters/heat exchangers ●
- Pumps ●
- Distillation units ●
- Reactors ●
- …

Actions:

- Heat exchange
- Material transport
- Separation
- Mixing
- …

Unit Operations:

- Unit Operations is a method of analysis and design of chemical engineering processes in terms of individual tasks/operations

- It is a way of organizing chemical engineering knowledge into groups of individual tasks/operations

- A unit operation: basic step in a chemical engineering process

Unit Operations: Classification

Fluid flow processes

- fluid transport
- solids fluidization
- mixing

Heat transfer processes

- heating/cooling
- evaporation/condensation

Mass transfer processes

- absorption
- distillation
- extraction
- adsorption
- drying

Thermodynamic processes

- liquifaction
- refrigeration

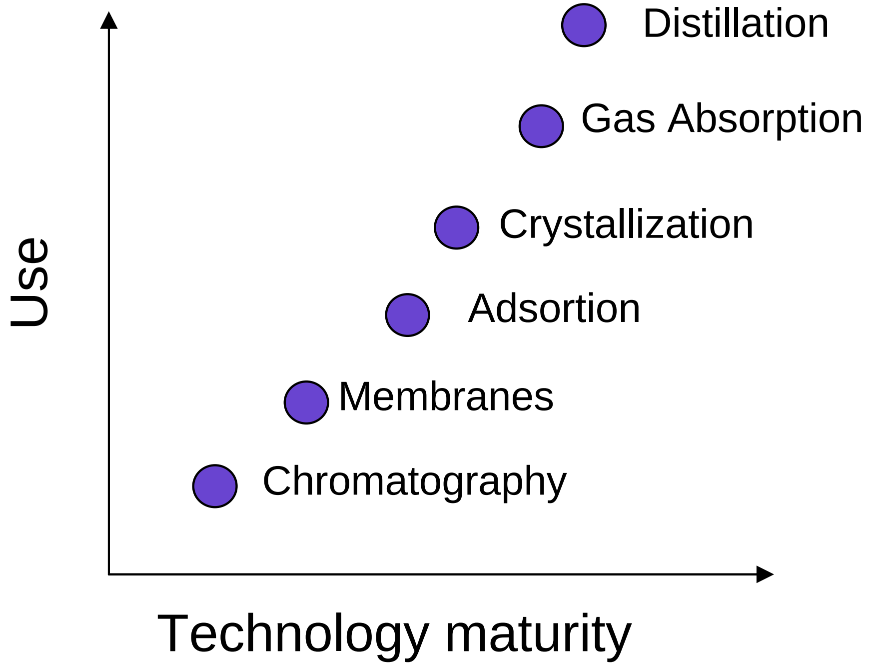
Mechanical processes

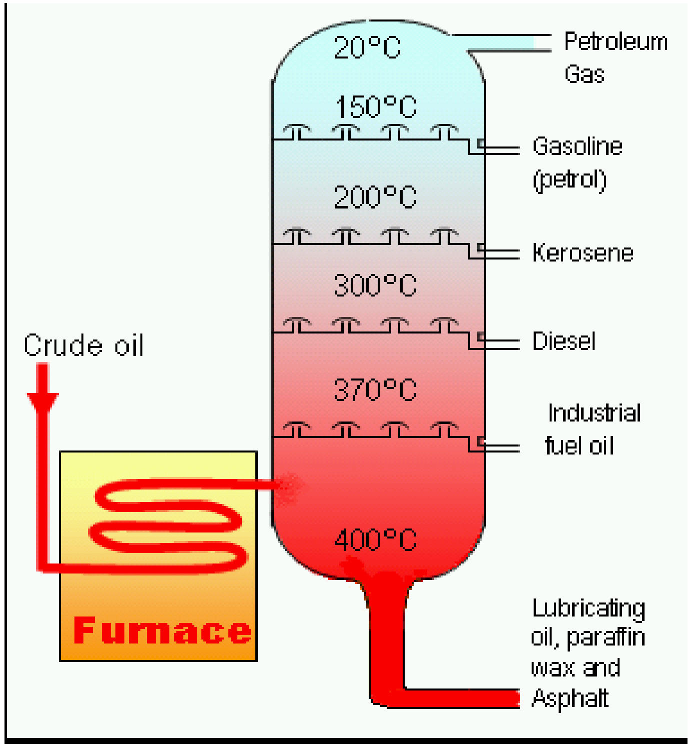
- crushing
- sieving
- solid transportation

Separation processes:
take a mixture of components and produce one or more products with desired composition/purity

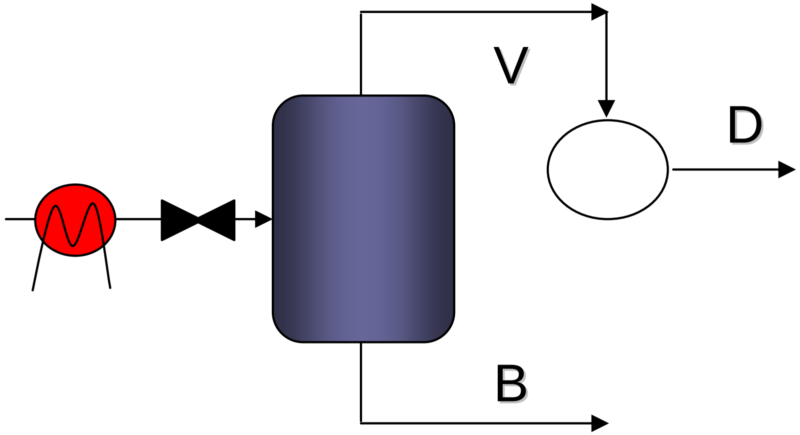
Chemical separation processes

- play a central role in chemical engineering





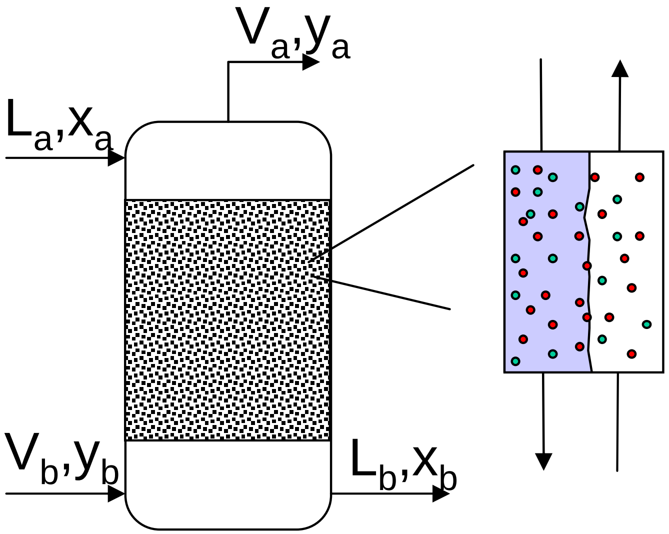
Chemical separation processes: required background



- How do we know that at pressure P and temperature T, vapour and liquid phase are present in the system?

- What is the composition of the phases?

Chemical engineering thermodynamics



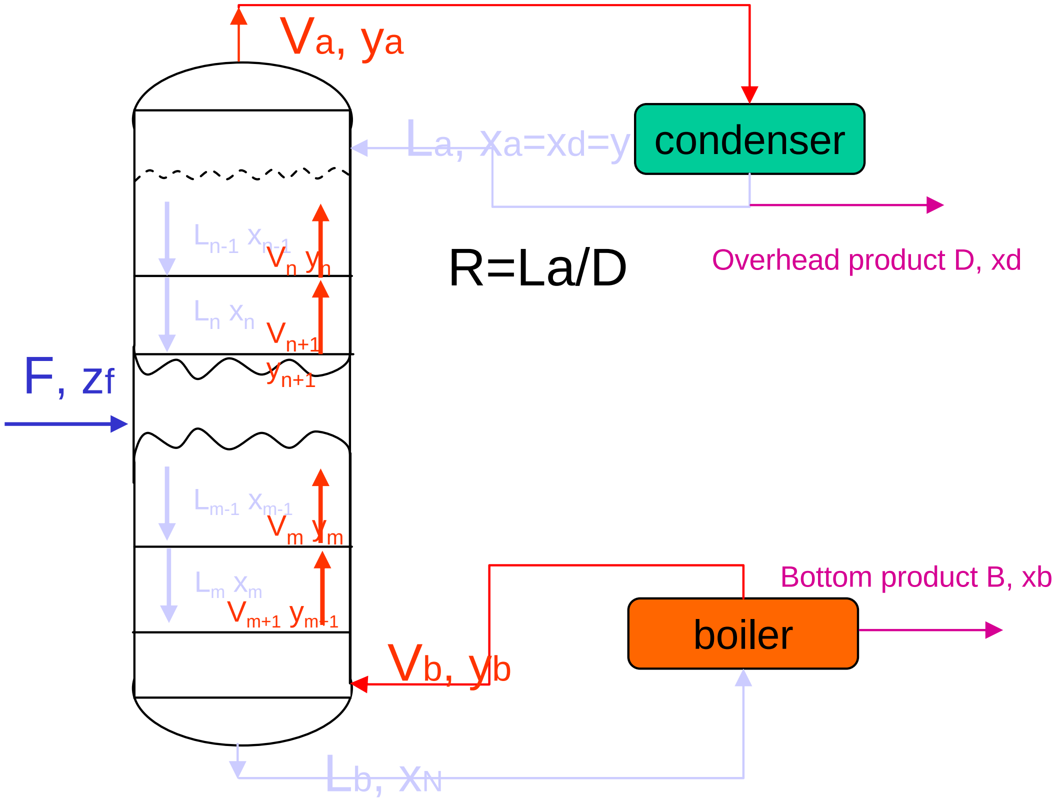
- How do we know the amount of mass exchanged by two phases?

- What is the new composition of the phases?

Mass transfer methods

Distillation processes

Distillation is a process where a feed mixture of two or more components is separated into products, of compositions different from the feed. This process takes advantage of the differences in distribution of components between the vapour and liquid phase.

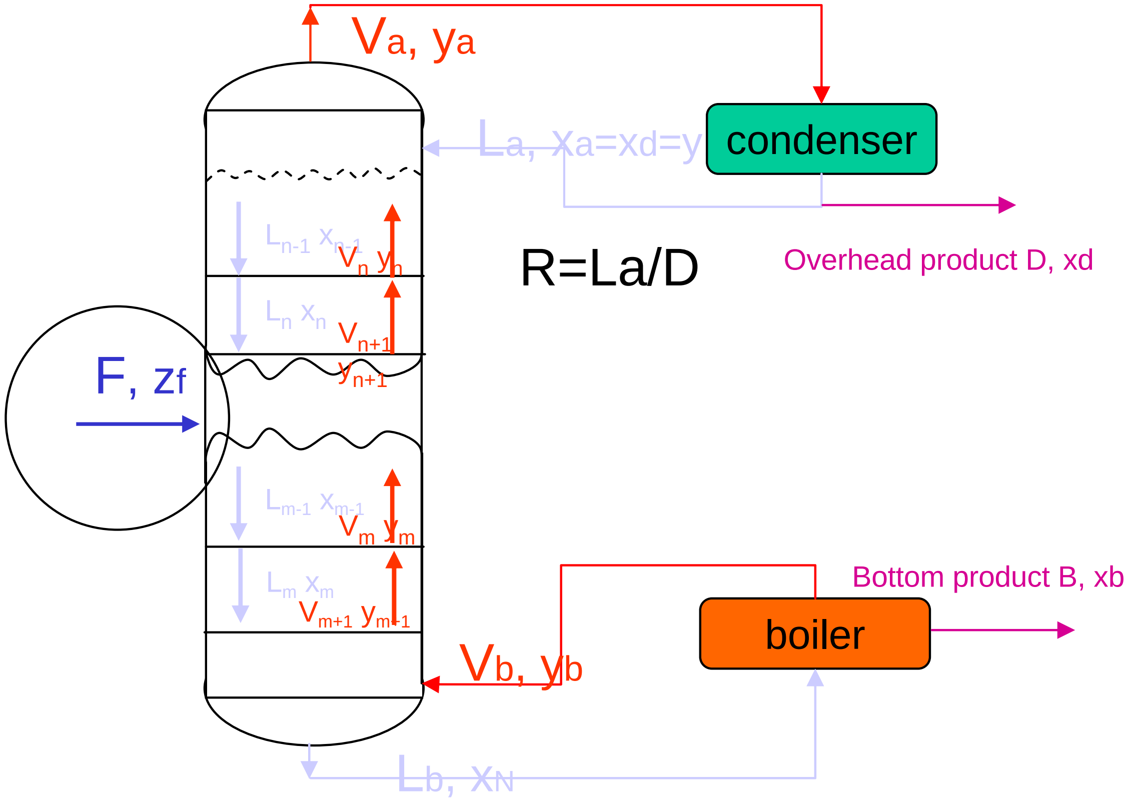


Distillation processes

The feed is material is introduced at one or more points along the column.

Liquid runs down the column from tray to tray, where as vapour is ascending along the column.

At each tray vapour and liquid contact and mix with each other

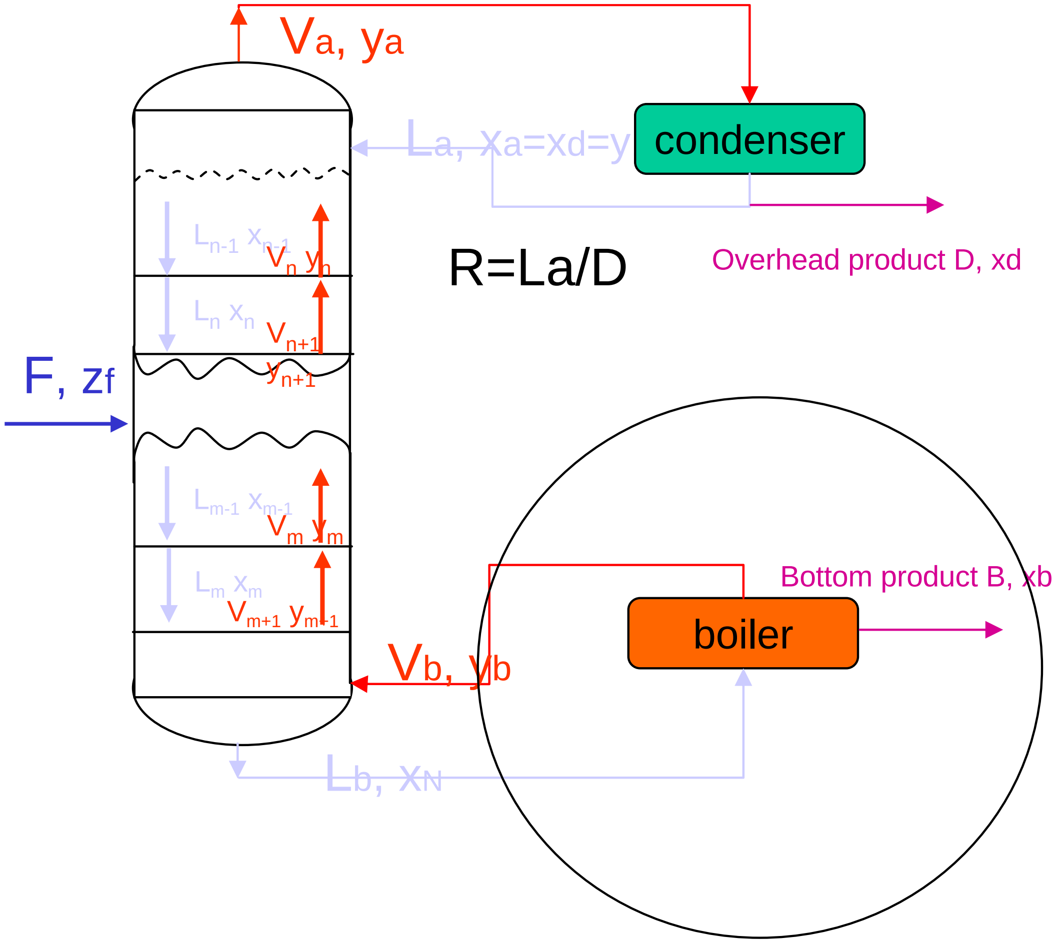


Distillation processes

Liquid at the bottom of the column is partially vaporized in a **heated reboiler.**

The boil-up is send back to the column.

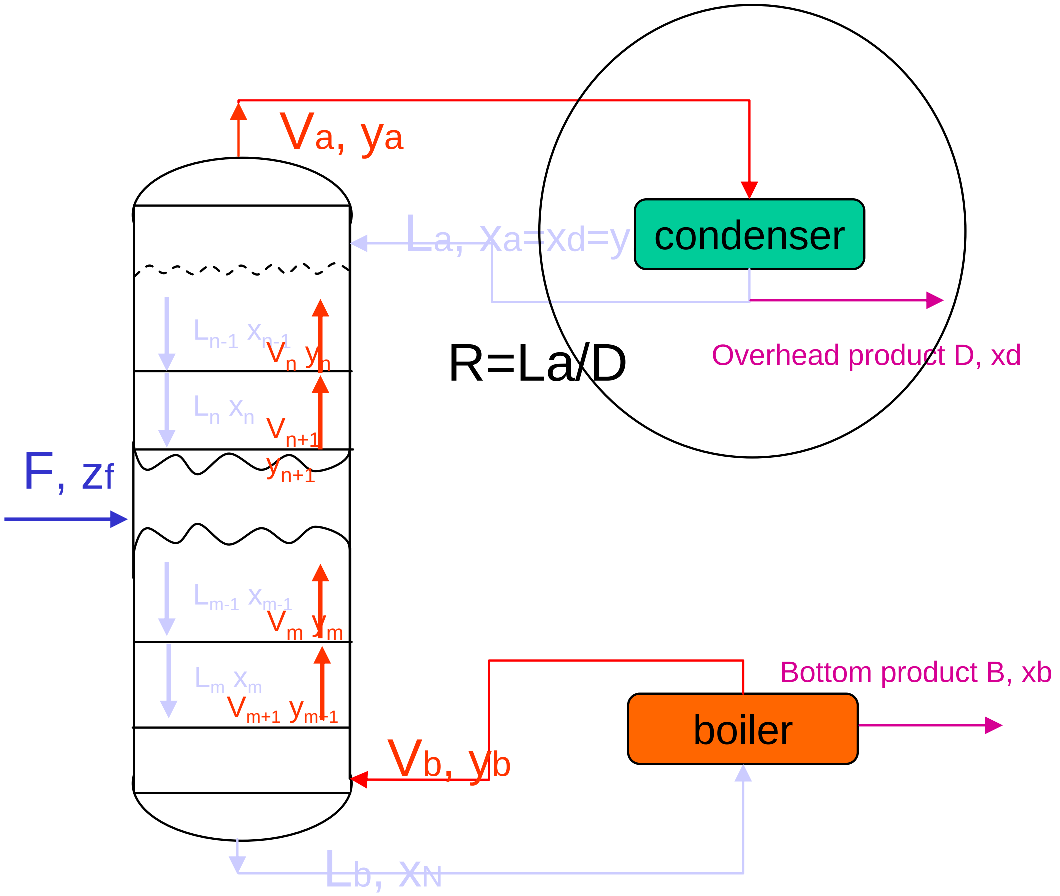
The rest is withdrawn as bottoms, or bottoms product



Distillation processes

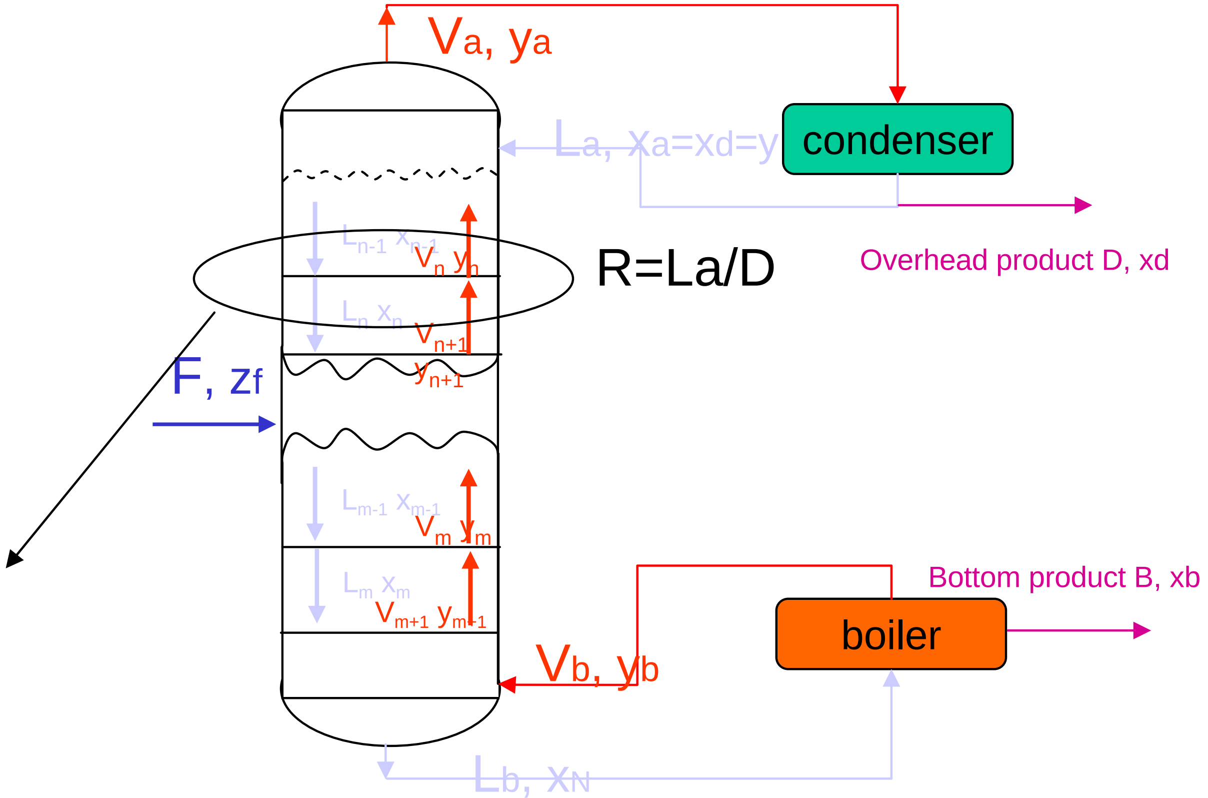
Vapour at the top of the column is cooled and condensed in the **overhead condenser.**

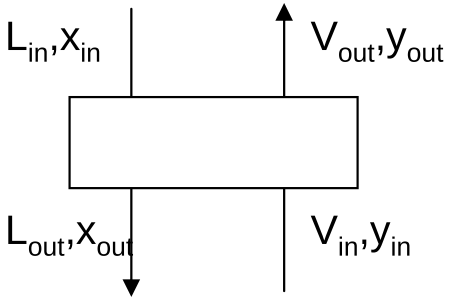
Part of this liquid is returned back to the column and the rest is withdrawn as distillate or overhead product



Distillation processes

At each stage of the column two phases come in contact with each other, mix, approach thermal and composition equilibrium to the extent which depends on the efficiency of the contact stage

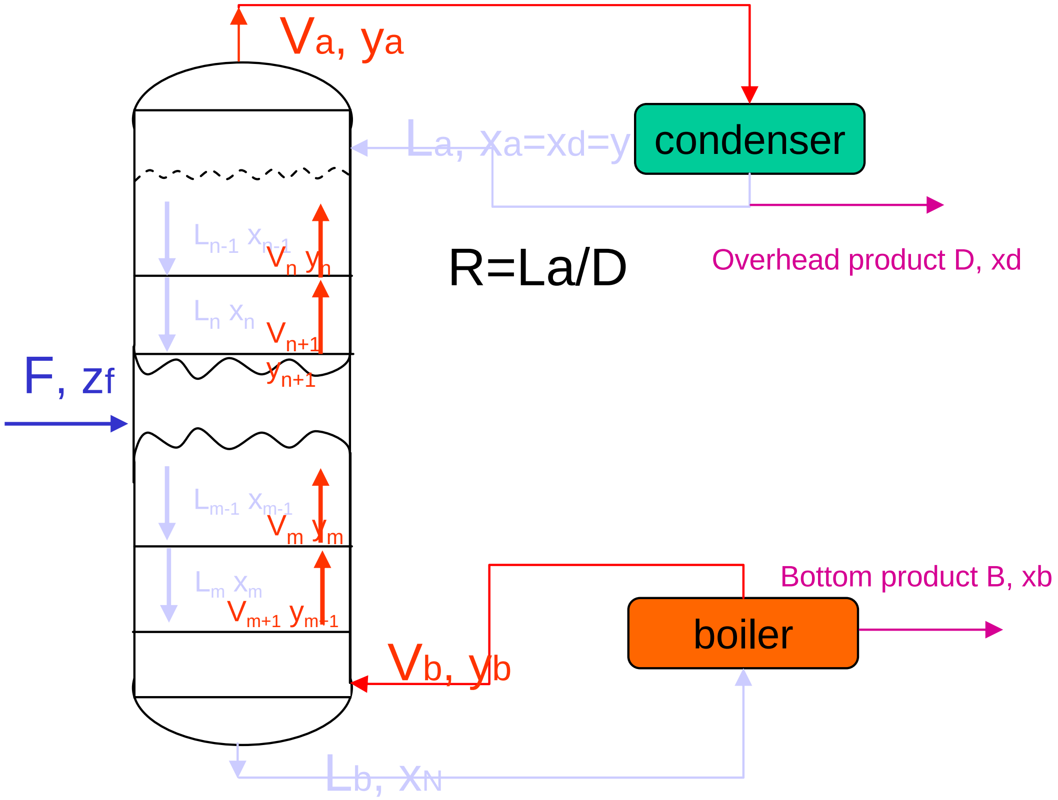




Distillation processes

The lighter component tends to accumulate in the vapour phase

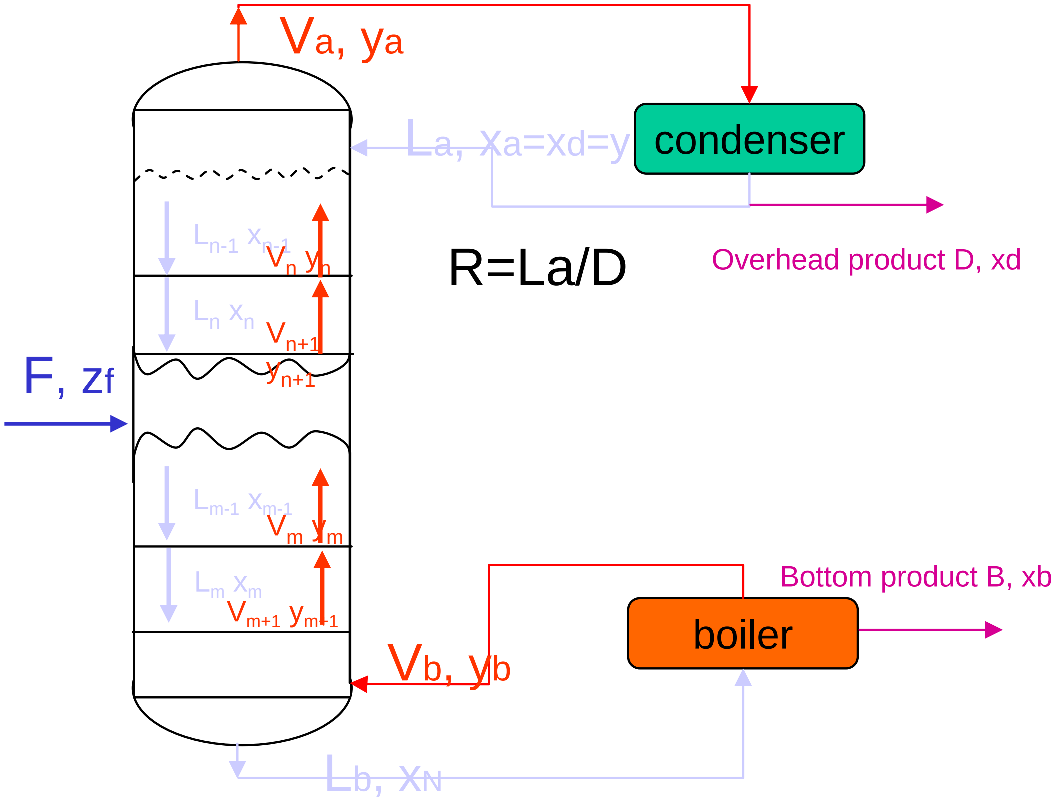
The heavier component tends to accumulate in the liquid phase



Distillation processes

In general, the overall separation process depends on:

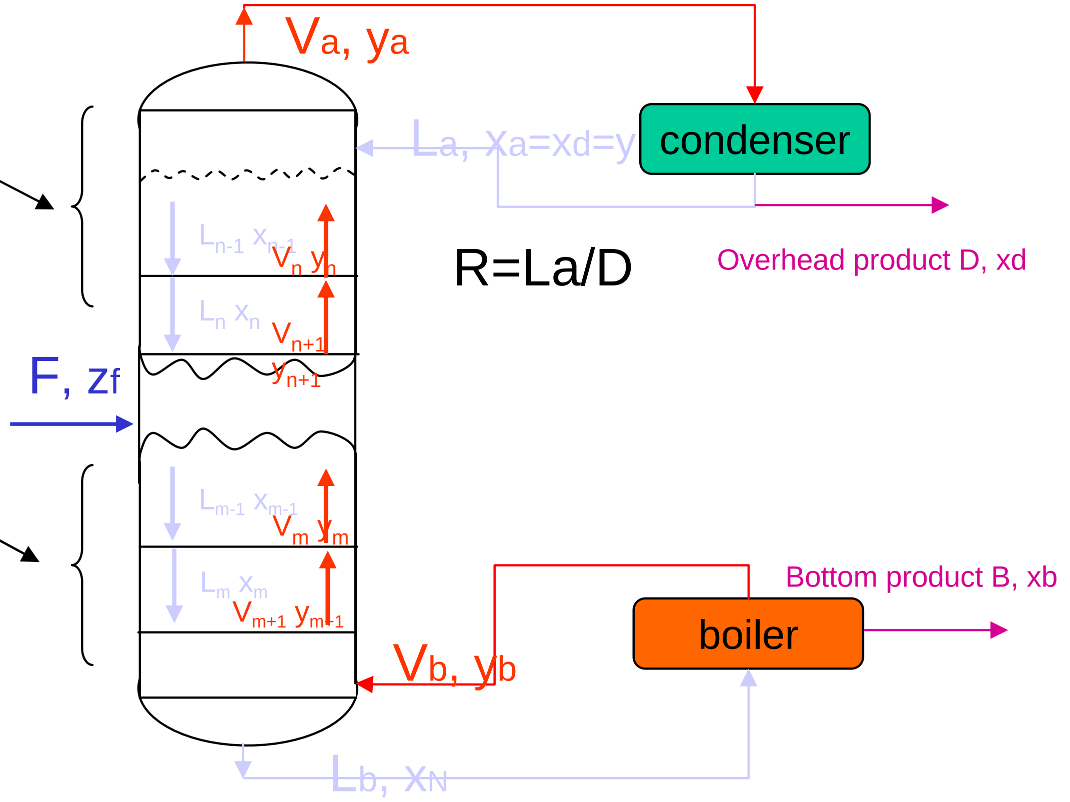
- **relative volatilities**
- **number of contacting stages**
- **ratio of liquid and vapour flowrates**



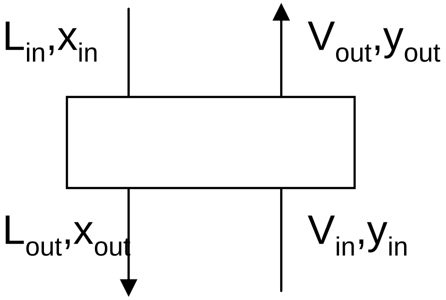
Distillation processes

If the feed is introduced at one point, it divides the column into a **rectifying** and **stripping** sections

But usually there are multiple feed location and various side streams



Definition of a stage in a process



A single stage is a device or a subunit of the process, where two (or more) phases of a different composition come in contact with each other, exchange and leave with new compositions

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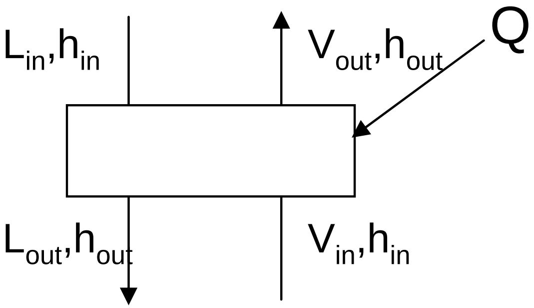
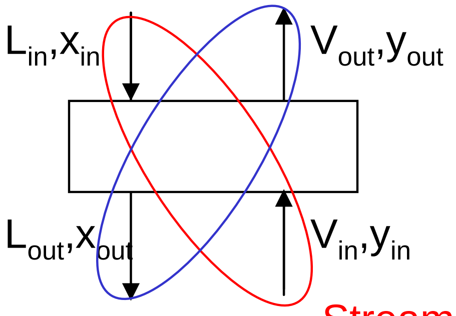
- Mass balance
  - Overall $L_{in} + V_{in} = L_{out} + V_{out}$
  - Components $L_{in} x_{in} + V_{in} y_{in} = L_{out} x_{out} + V_{out} y_{out}$

- Energy balance



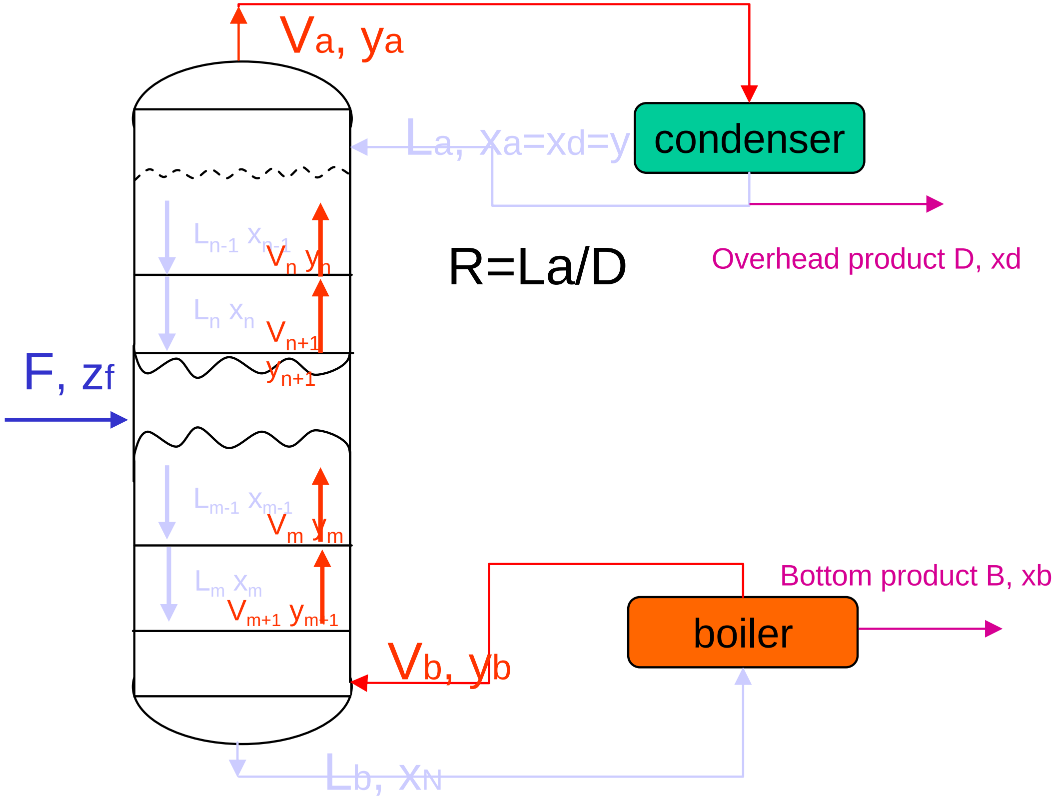
$$L_{in} h_{in} + V_{in} h_{in} + Q = L_{out} h_{out} + V_{out} h_{out}$$

Equilibrium stage processes



Streams *leaving* the stage are in thermodynamic equilibrium with each other

Streams coming to the stage: not in equilibrium



R=La/D

The idea is then to consider a hypothetical column, composed of equilibrium stages

This idealistic design can be converted to the actual design via analysis of tray efficiency

Distillation process design

Step 1: Thermodynamics data and methods to predict equilibrium phase compositions

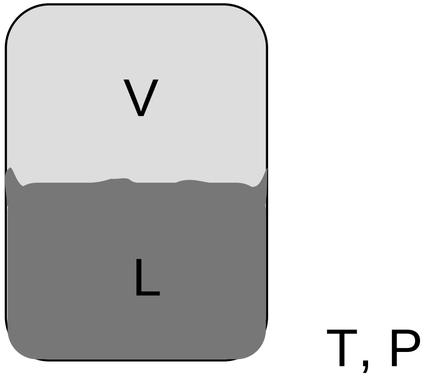
Step 2: Design of equilibrium stage separation

- Design problem type 1: To determine the number of equilibrium stages required to accomplish the desired separations

- Design problem type 2: Given a particular column design, determine separation that can be accomplished

Step 3: Develop an actual design by applying the stage efficiency analysis to equilibrium stage design

Thermodynamic considerations and phase equilibria



The basic task: to determine the equilibrium relationship between T, P, y_i, x_i

- Tabulated data
- Analytical expressions
- Simplified models

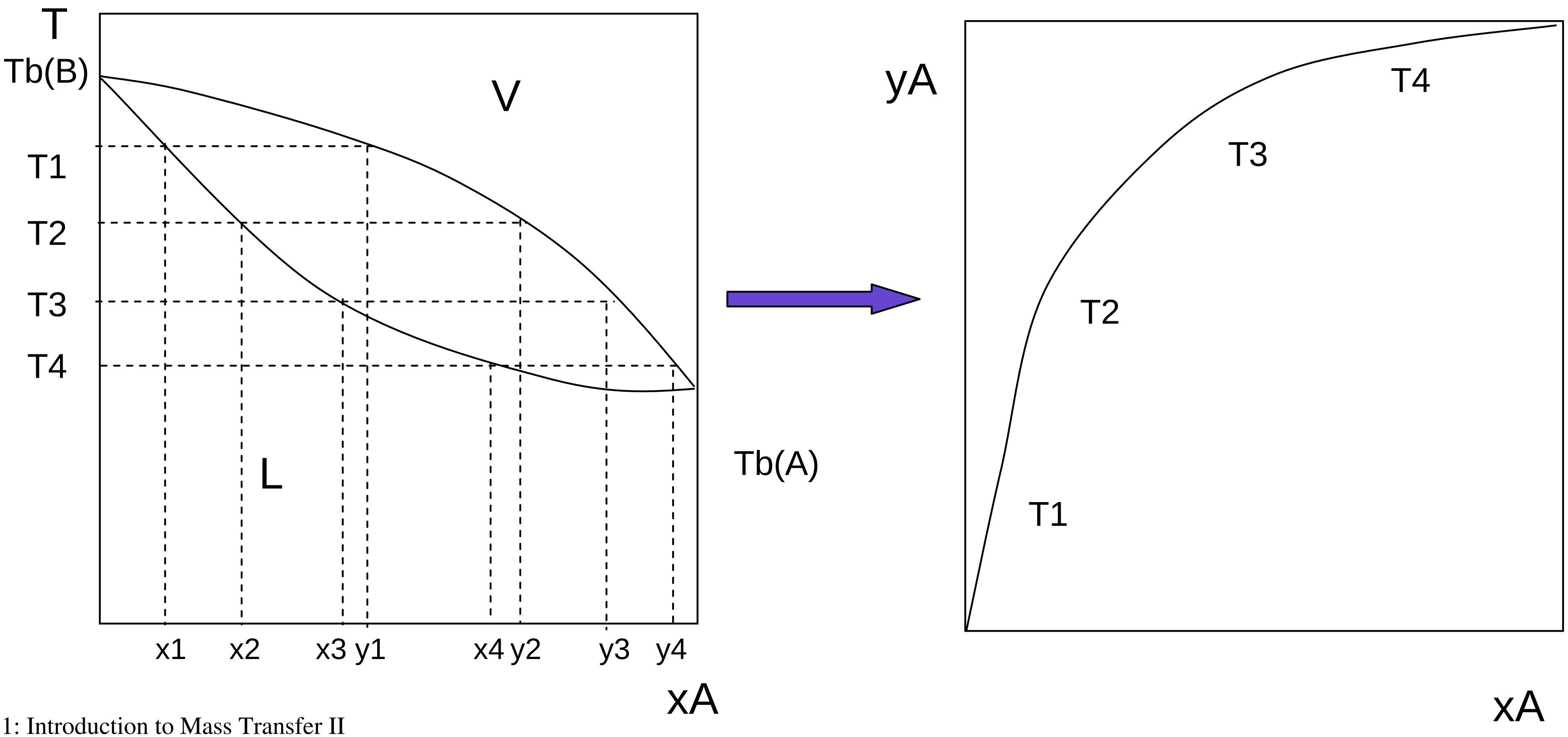
Thermodynamic considerations and phase equilibria: Binary fluids

For a binary mixture specification of pressure and temperature fixes the equilibrium vapour and liquid compositions

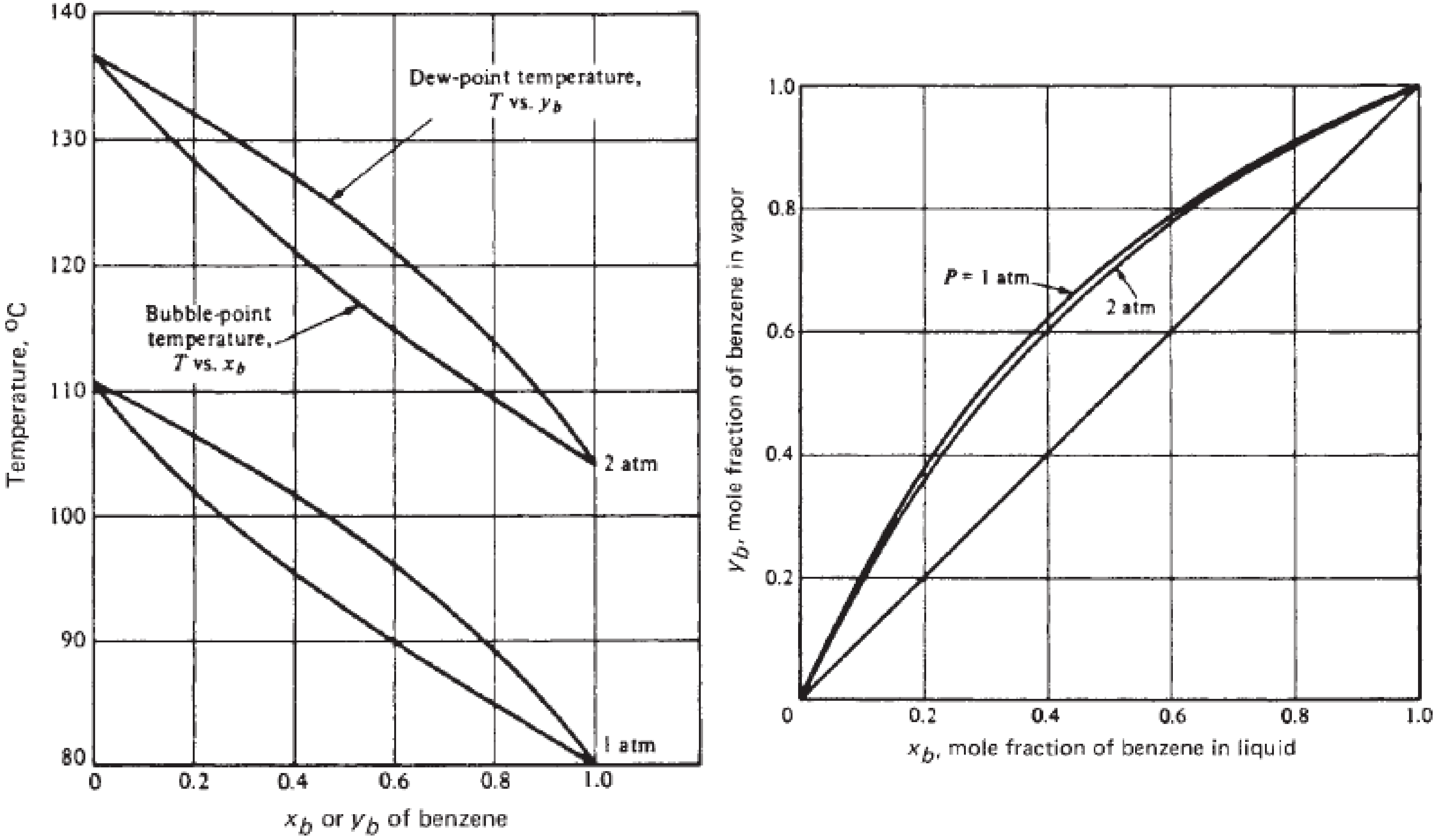
Experimental data is frequently presented as vapour mole fraction y and liquid mole fraction of one of the components over a range of temperatures at fixed pressure (tables, graphs)

Thermodynamic considerations and phase equilibria: Binary fluids

Lets consider a binary mixture AB, where B is a heavy component (high boiling point) and a is a light component (low boiling point). A T-x phase diagram of AB mixture, where x is a mole fraction of component a might look like this at some constant pressure P. This phase diagram can be also transformed in y-x diagram where composition of vapour phase in terms of mole fraction of component A is plotted as function of the liquid phase composition.

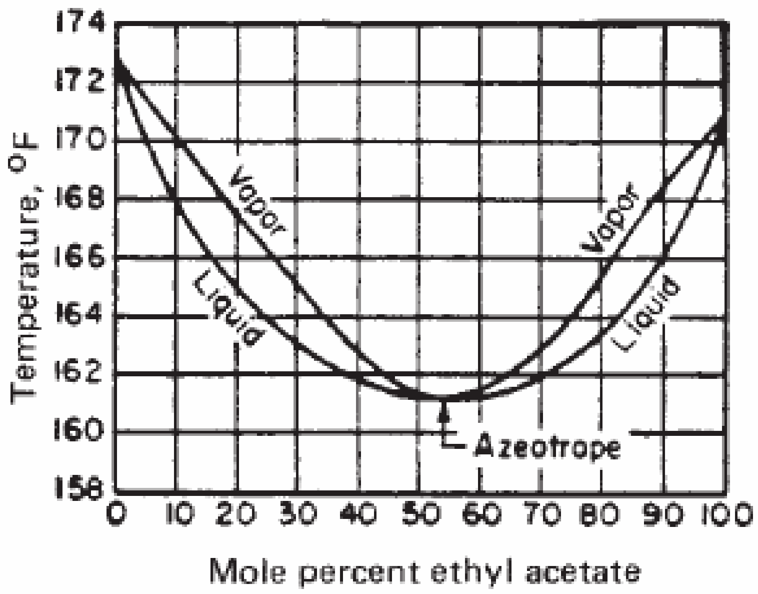


Binary fluids: Examples

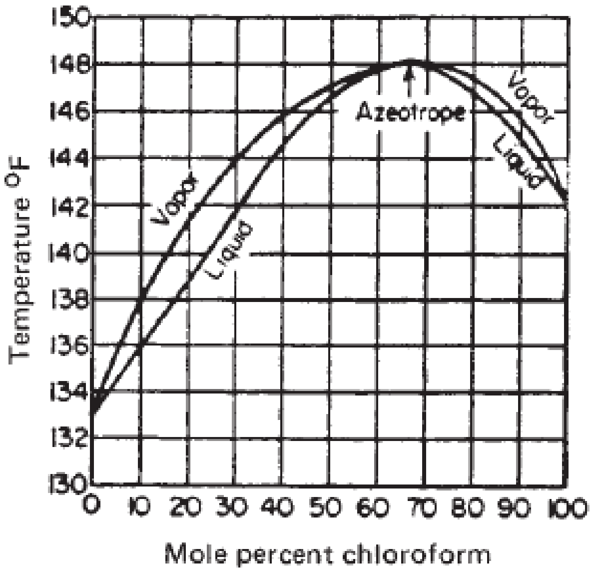


Benzene-toluene binary mixture

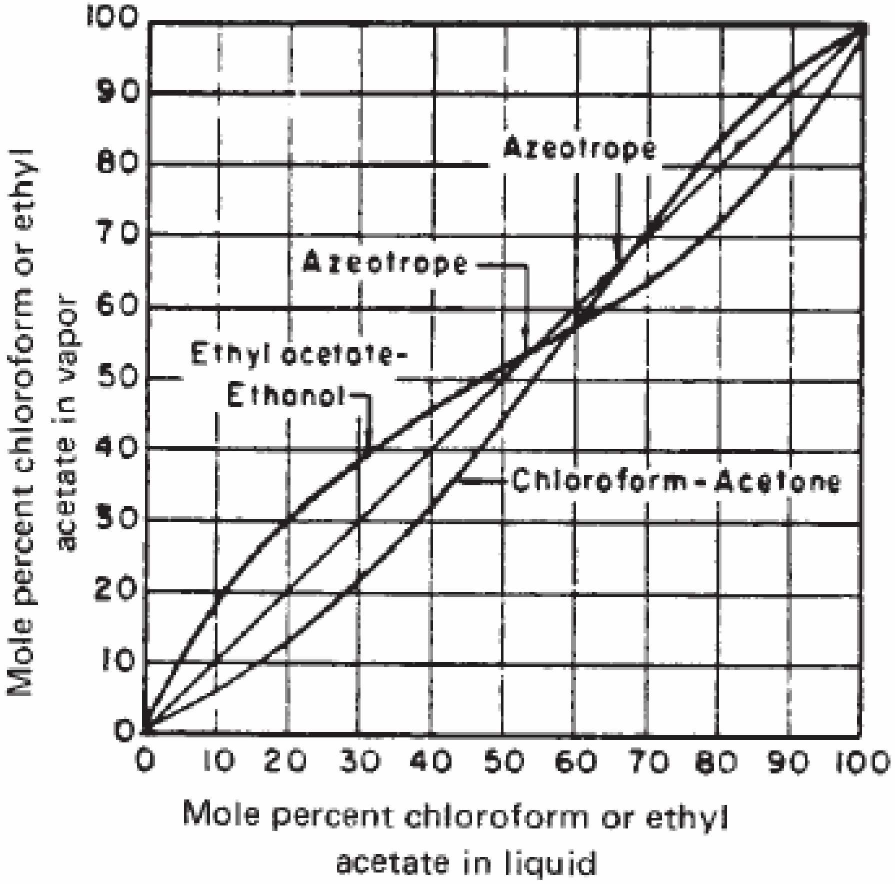
Binary fluids: Examples of strong non-ideality



Ethyl acetate – ethanol, P=1atm



Chlorophorm – acetone, P=1atm



Thermodynamic considerations and phase equilibria: multicomponent mixtures

For multicomponent mixtures simple graphical representations of vapour-liquid equilibria data do not exist

Most often such data (including binary systems) is represented in terms of K values defined as:

$$K_i = y_i / x_i$$

correlated empirically or theoretically in terms of temperature pressure and composition

The ratio of two K-values, or relative volatility, indicates the relative ease or difficulty of separating components *i* and *j*

$$\alpha_{ij} = \frac{K_i}{K_j} = \frac{y_i / x_i}{y_j / x_j}$$

Light hydrocarbon mixtures: DePriester charts (1953)

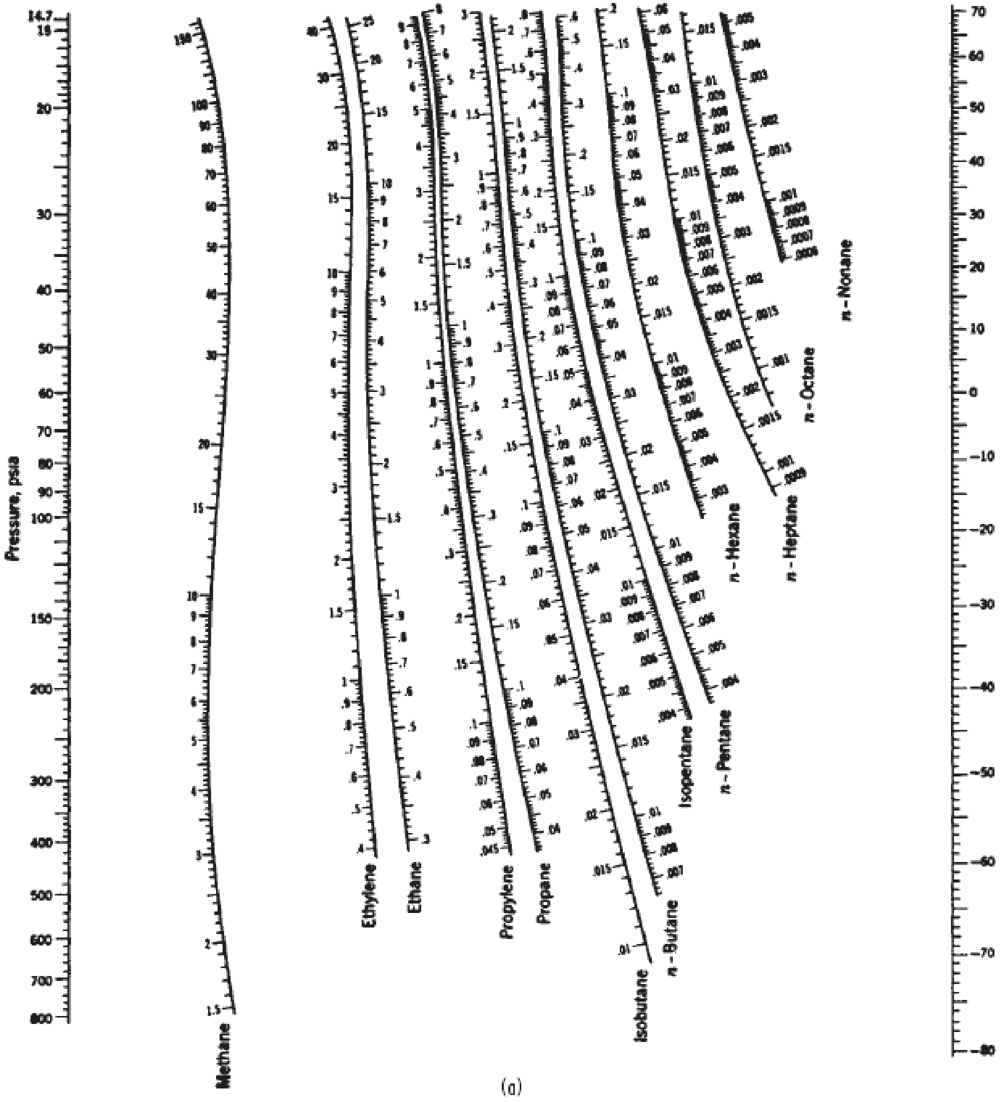


FIG. 13-14 *K* values (*K* = *y*/*x*) in light-hydrocarbon systems. (*a*) Low-temperature range. [*DePriester*, Chem. Eng. Prog. Symp. Sec. 7, *49, 1* (1953).]

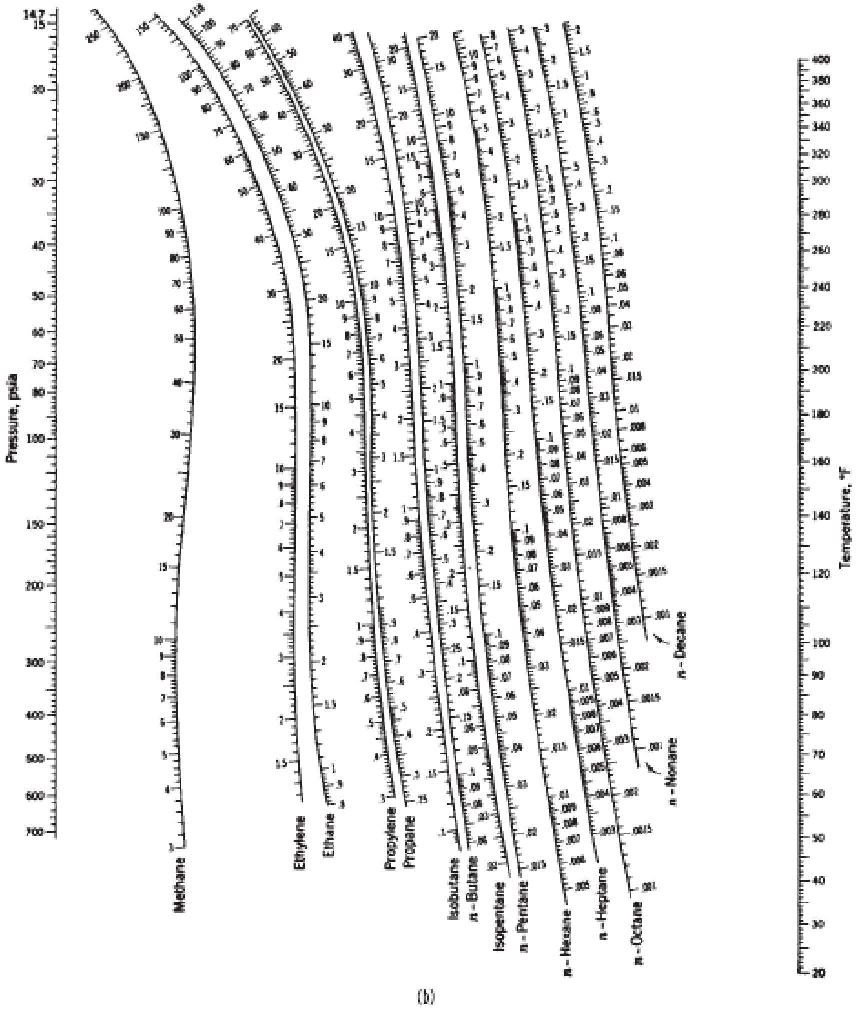


FIG. 13-14 (*Continued*) *K* values (*K* = *y*/*x*) in light-hydrocarbon systems. (*b*) High-temperature range. [*DePriester*, Chem. Eng. Prog. Symp. Sec. 7, *49, 1* (1953).]

Light hydrocarbon mixtures: DePriester charts (1953)

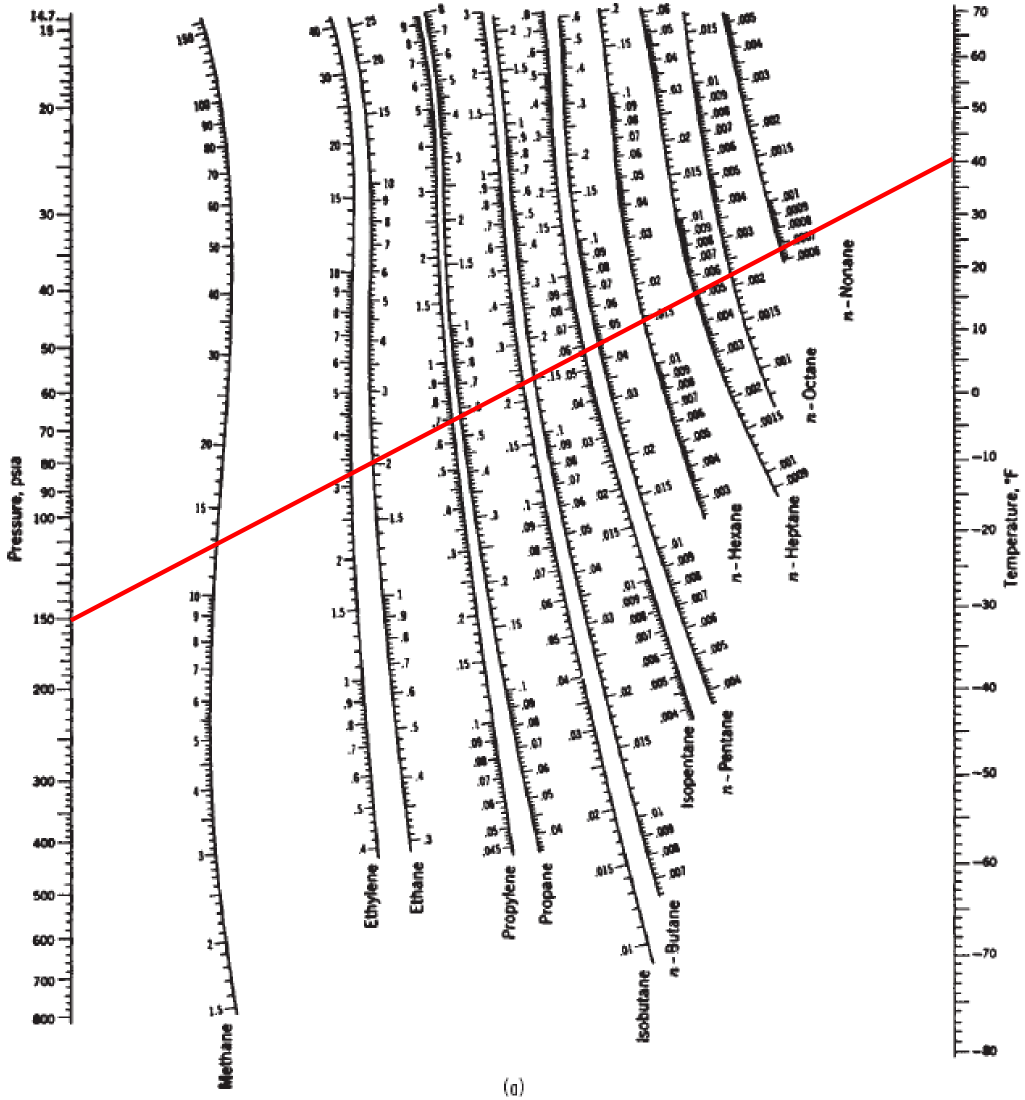


FIG. 13-14 *K* values ($K = y/x$) in light-hydrocarbon systems. (*a*) Low-temperature range. [*DePriester*, Chem. Eng. Prog. Symp. Sec. 7, *49*, *1* (1953).]

Thermodynamics

Next Lecture: Absorption

Before Next lecture Read

- Review Thermodynamics
- Equilibrium
- Entropy
- Solution Thermodynamics
- Activity and Activity Coefficients
- Equilibrium Phase Diagrams