Equipment Fundamentals: Separation & Fractionation

Chapters 4 & 5

With thanks to Tim Rollenhagen, Anadarko

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Topics

Fundamentals of separation

- Volatility differences
  - flash calculations
- Multi-stage fractionation
  - Distillation
- Other
  - Adsorption
  - Membranes

Equipment

- Gas/oil/water separators
  - Filters & coalescers
  - Cyclone separators
- Distillation columns
  - Auxiliary equipment
    - Condenser
    - Reboiler
  - Trays or packing?
- Adsorption
  - Mole sieves
- Membranes

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Fundamentals

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“Flash calculation” – Description of VLE

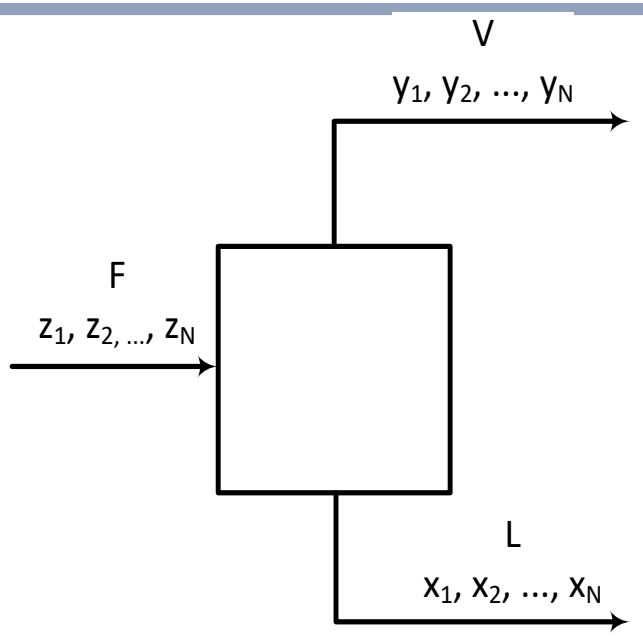
Incorporate the mass balance equation with equilibrium constraints

Given a set of equilibrium coefficients, the Ki values, determine the overall molar phase fraction so that the residual equation is equal to zero

- There is a two phase situation if the phase fraction is between 0 and 1
- If the phase fraction is outside this range then there is only a single phase. The phase condition corresponds to the value of R(0) or R(1) that is closer to zero

Can get the expected equations describing the bubble & dew points by setting ℓ=0 or ℓ=1

Ideal gas & liquid: $K_i \approx P_i^{vap}(T) / P$



$$R(\ell) = \sum_{i=1}^{N} \frac{z_i (1 - K_i)}{\ell (1 - K_i) + K_i} = 0 \quad \text{with} \quad \ell \equiv \frac{L}{F}$$

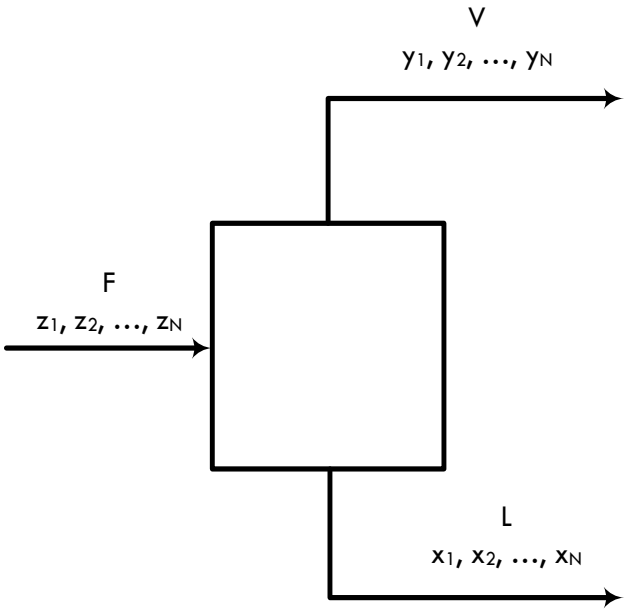
or

$$R(\beta) = \sum_{i=1}^{N} \frac{z_i (K_i - 1)}{1 + \beta (K_i - 1)} = 0 \quad \text{with} \quad \beta \equiv \frac{V}{F}$$

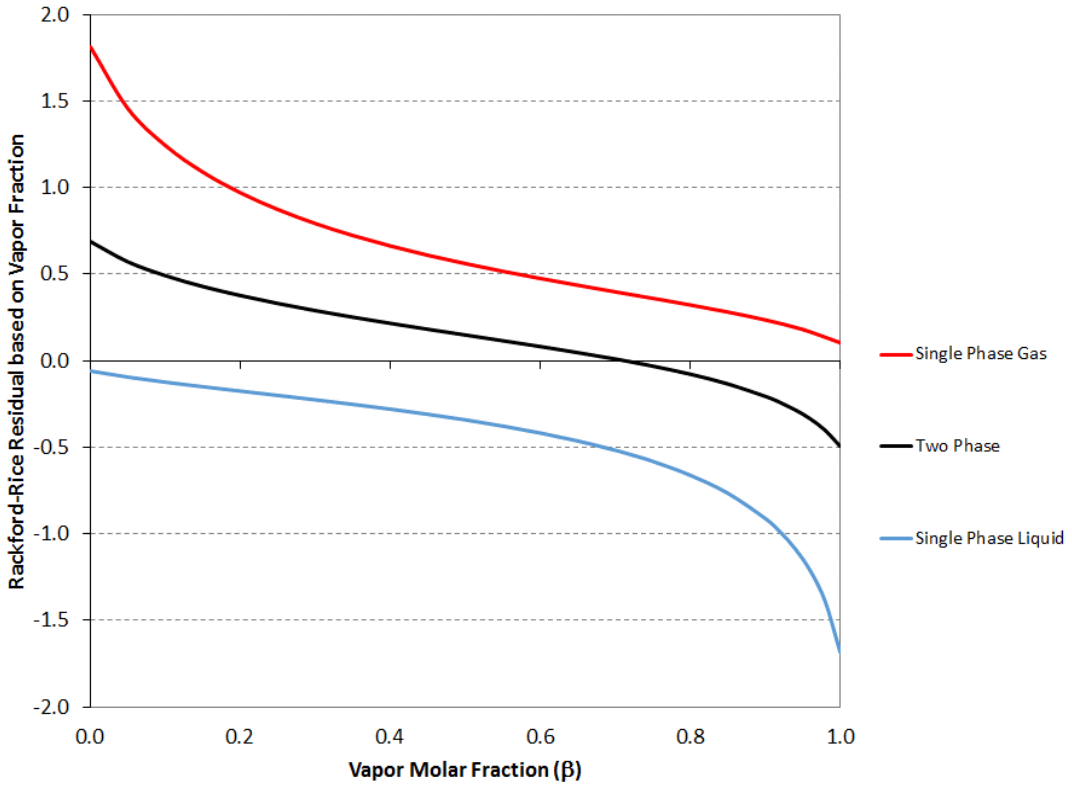
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Rackford-Rice Flash Calculation Curves



$$R(\beta) = \sum_{i=1}^{N} \frac{z_i (K_i - 1)}{1 + \beta (K_i - 1)} = 0 \quad \text{with} \quad \beta \equiv \frac{V}{F}$$



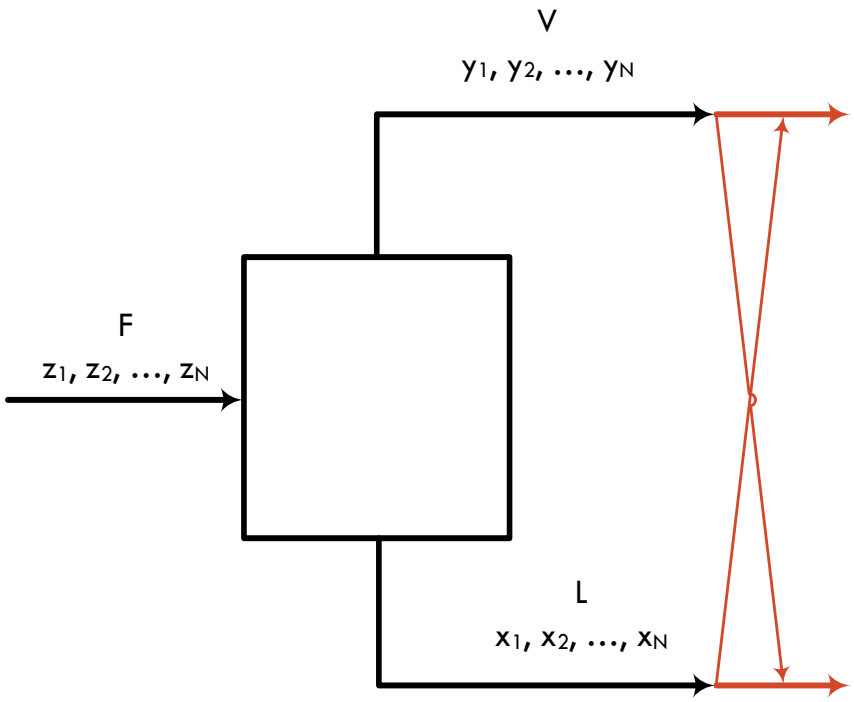
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Entrainment

Small amounts of the coexisting phase gets carried along because of poor physical separation of the phases

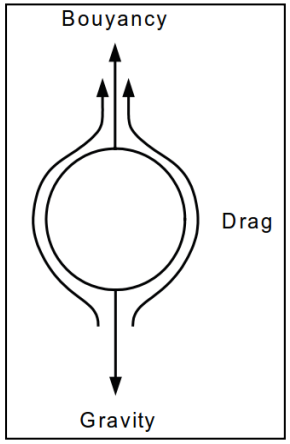
Cannot be predicted from thermodynamics because it is dependent on the flow characteristics of the equipment



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Gravity Settling Theory

Dispersed droplets will settle out from a continuous phase if the gravitational force overcomes the buoyancy & drag forces on the droplets

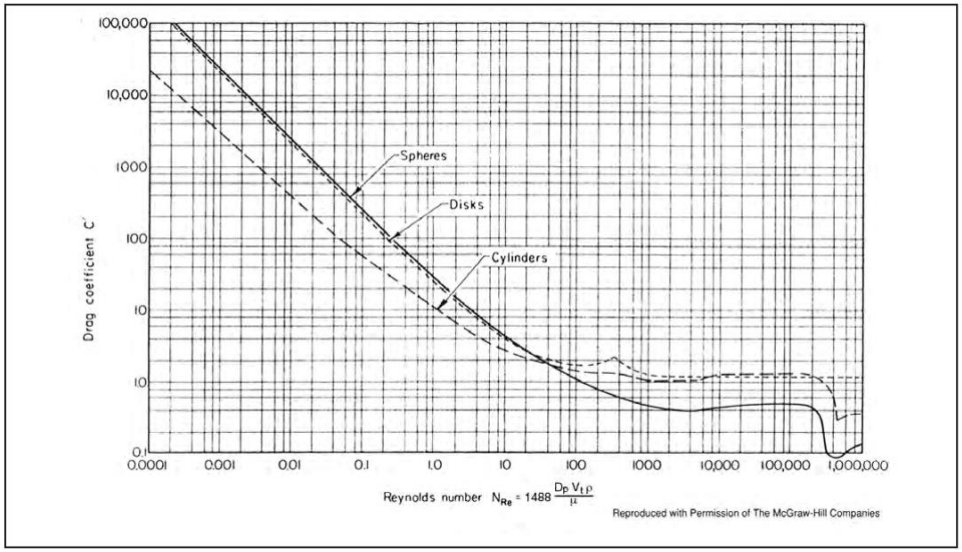


The droplet's terminal velocity typically calculated assuming it is solid, rigid sphere

$$V_t = \sqrt{\frac{4gD_p\left(\rho_p - \rho_c\right)}{3\rho_c C'}}$$

The drag coefficient can be determined using a definition of Reynolds number based on particle size but fluid properties of the continuous phase

$$N_{\text{Re}} = \frac{D_p V_t \rho_c}{\mu_c}$$

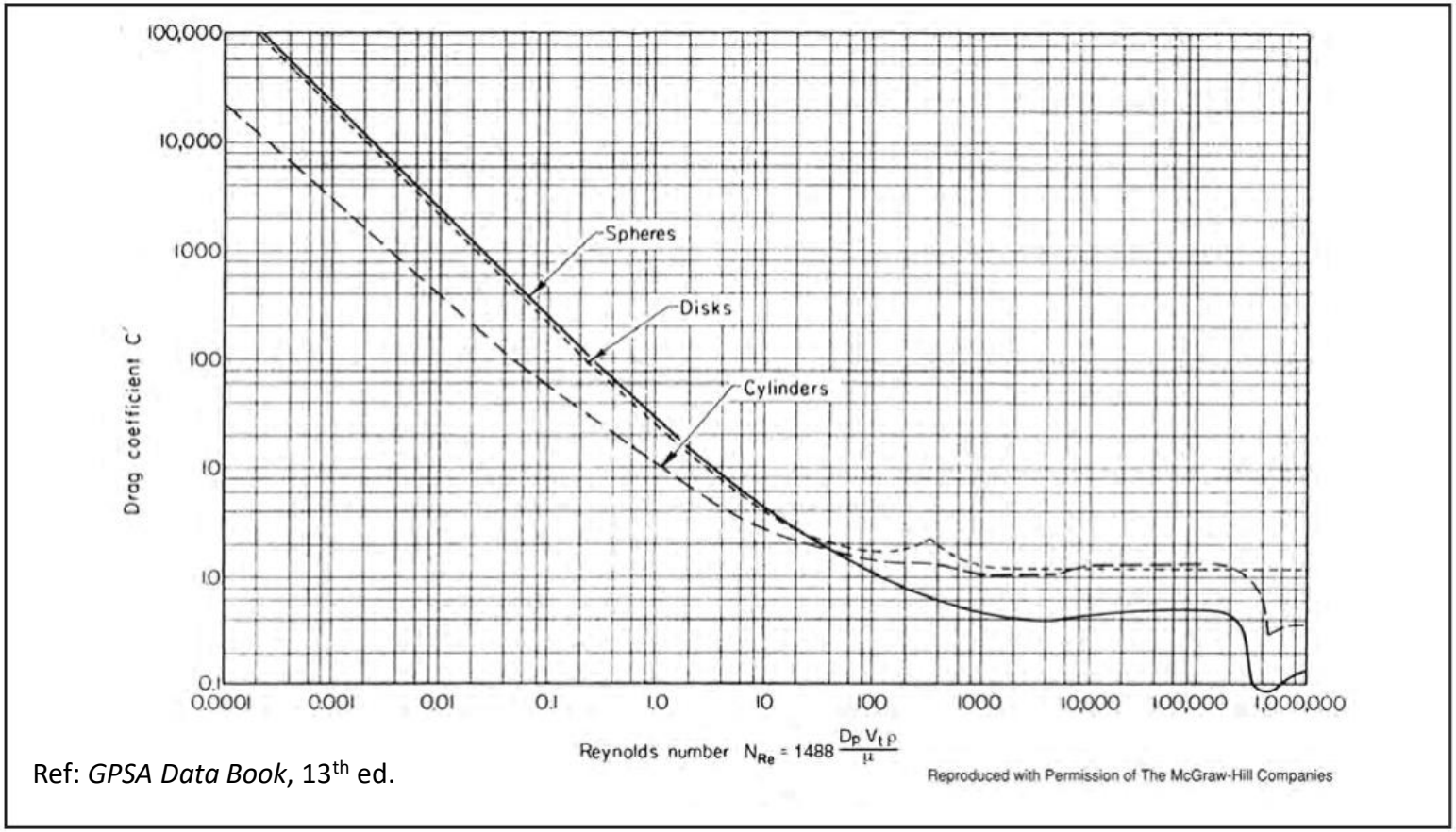


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Drag Coefficient for Spherical Particles

FIG. 7-5
Drag Coefficient and Reynolds Number for Spherical Particles



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Fractionation as Cascade of Equilibrium Stages

FIG. 19-2
Fractionation Schematic Diagram

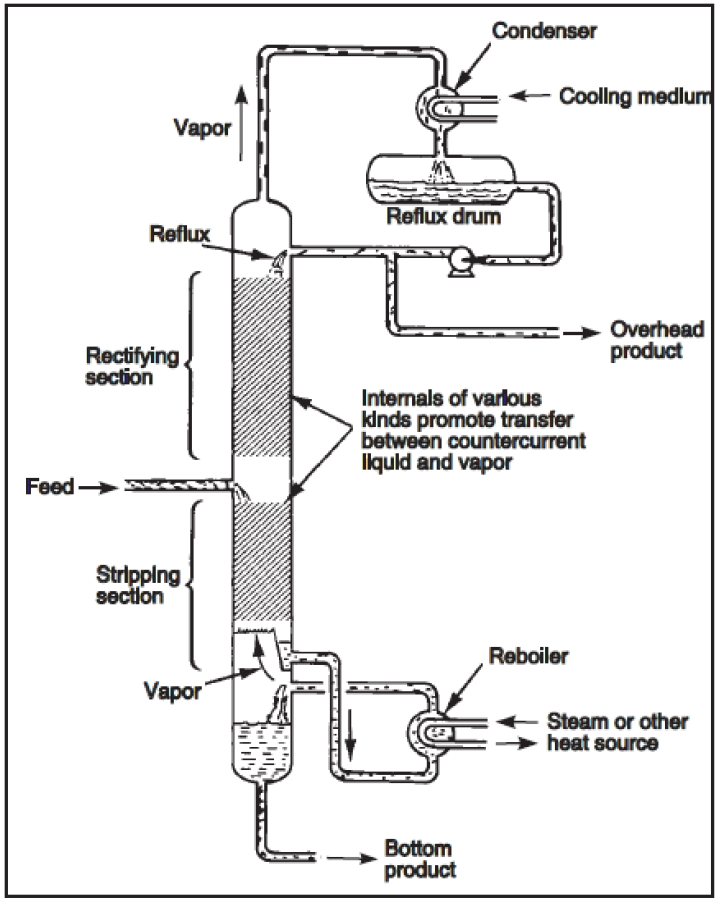
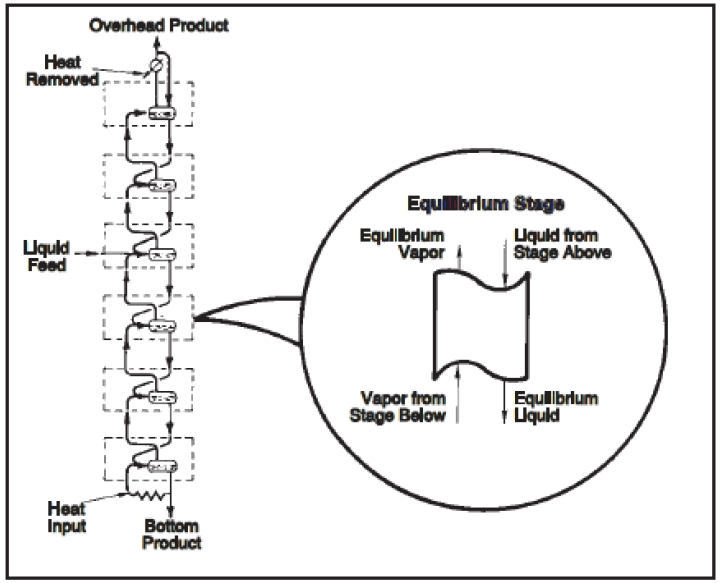


FIG. 19-3
Basic Fractionation Model



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Fractionation Key Concepts

Separation due to differences in boiling points/relative volatilities

- Light key & lighter to the overhead
- Heavy key & heavier to the bottoms

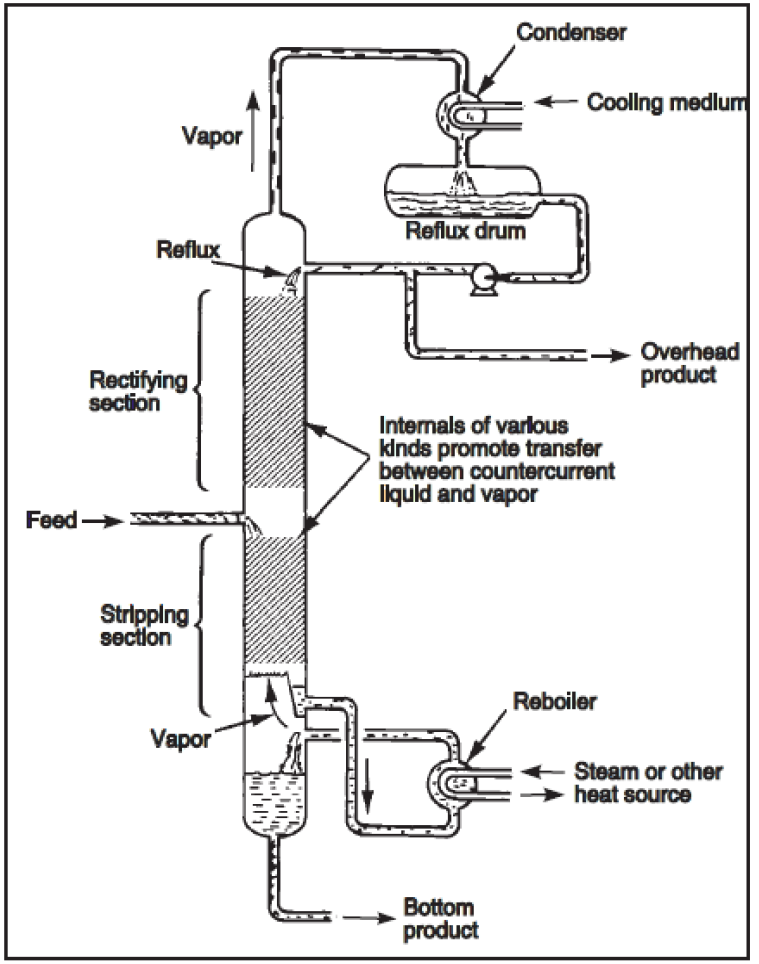
Sections

- Rectifying section – heavy key & heavier absorbed into falling liquid
- Stripping section – light key & lighter stripped by rising gas

Heat exchangers may provide vapor & liquid traffic

- Heated bottoms generates vapor for stripping section
- Condenser cools & condenses overhead vapor generating liquid for rectifying section

FIG. 19-2
Fractionation Schematic Diagram



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Separation, Reflux, & Number of Stages

During the design phase there is flexibility between the number of stages, the column "traffic" (i.e., reflux, boilup), & the degree of separation

- Trade off between CAPEX & OPEX

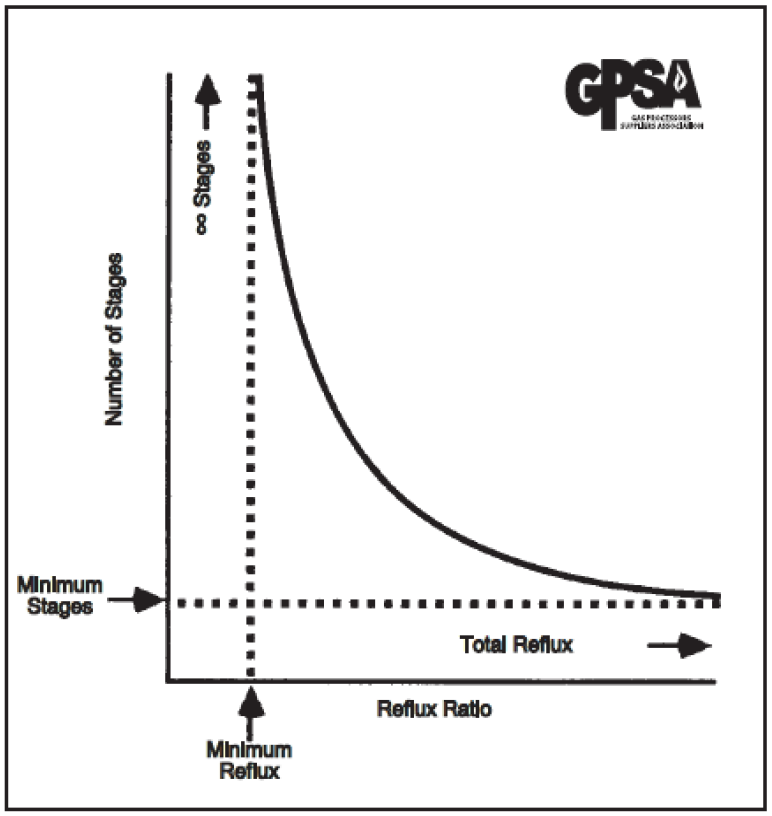
Correlations to determine the minimum stages & reflux

- Minimum stages @ infinite/total reflux – Fenske equation
- Minimum reflux @ infinite number of stages – Underwood equation

Typically design to operate at 1.2 to 1.3 times the minimum reflux

- Erbar-Maddox chart to estimate number of stages

FIG. 19-6
Relationship Between Reflux Ratio and Number of Stages



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Number Theoretical Stages vs. Actual Trays

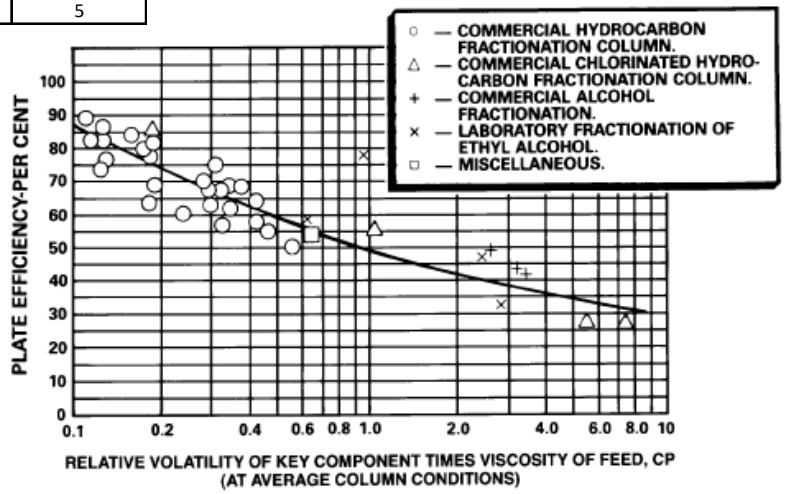
Column Service	Typical No. of Actual Trays	Typical Overall Efficiency	Typical No. of Theoretical Trays
Simple Absorber/Stripper	20 – 30	20 – 30	
Steam Side Stripper	5 – 7		2
Reboiled Side Stripper	7 – 10		3 – 4
Reboiled Absorber	20 – 40	40 – 50	
Deethanizer	25 – 35	65 – 75	
Depropanizer	35 – 40	70 – 80	
Debutanizer	38 – 45	85 – 90	
Alky DeiC4 (reflux)	75 – 90	85 – 90	
Alky DeiC4 (no reflux)	55 – 70	55 – 65	
Naphtha Splitter	25 – 35	70 – 75	
C2 Splitter	110 – 130	95 – 100	
C3 Splitter	200 – 250	95 – 100	
C4 Splitter	70 – 80	85 – 90	
Amine Contactor	20 – 24		4 – 5
Amine Stripper	20 – 24	45 - 55	9 – 12
Crude Distillation	35 – 50	50 – 60	20 – 30
Stripping Zone	5 – 7	30	2
Flash Zone – 1st draw	3 – 7	30	1 – 2
1st Draw – 2nd Draw	7 – 10	45 – 50	3 – 5
2nd Draw – 3rd Draw	7 – 10	50 – 55	3 – 5
Top Draw – Reflux	10 – 12	60 – 70	6 – 8
Vacuum Column (G.O. Operation)			
Stripping	2 – 4		1
Flash Zone – HGO Draw	2 – 3		1 – 2
HGO Section	3 – 5		2
LGO Section	3 – 5		2
FCC Main Fractionator	24 – 35	50 – 60	13 – 17
Quench Zone	5 – 7		2
Quench – HGO Draw	3 – 5		2 – 3
HGO – LCGO	6 – 8		3 – 5
LCGO – Top	7 – 10		5 – 7

Refinery Process Modeling
Gerald Kaes, Athens Printing Company, 2000, pg. 32

Viscosity	Maxwell	Drickamer & Bradford in Ludwig
cP	Ave Viscosity of liquid on plates	Molal Ave Viscosity of Feed
0.05	…	98
0.10	104	79
0.15	86	70
0.20	76	60
0.30	63	50
0.40	56	42
0.50	50	36
0.60	46	31
0.70	43	27
0.80	40	23
0.90	38	19
1.00	36	17
1.50	30	7
1.70	28	5

Rules of Thumb for Chemical Engineers, 4th ed.
Carl Branan, Gulf Professional Publishing, 2005

Engineering Data Book, 12th ed.
Gas Processors Association, 2004



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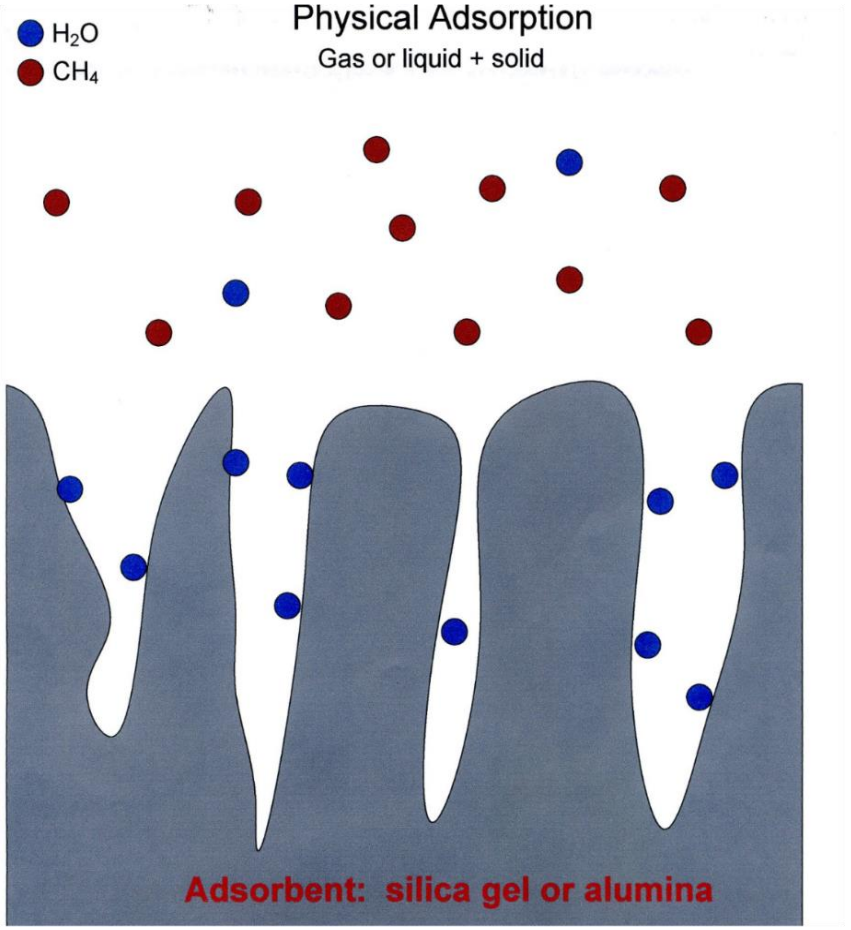
Other Separation Processes – Adsorption

Molecules get caught up with the adsorbing material allowing the non-adsorbed molecules to pass through with less hindrance

The retained molecules need to be driven off of the adsorbing material to regenerate the adsorbent

- PSA – Pressure Swing Adsorption
- TSA – Temperature Swing Adsorption

Separation can be based on molecular size, chemical type, …



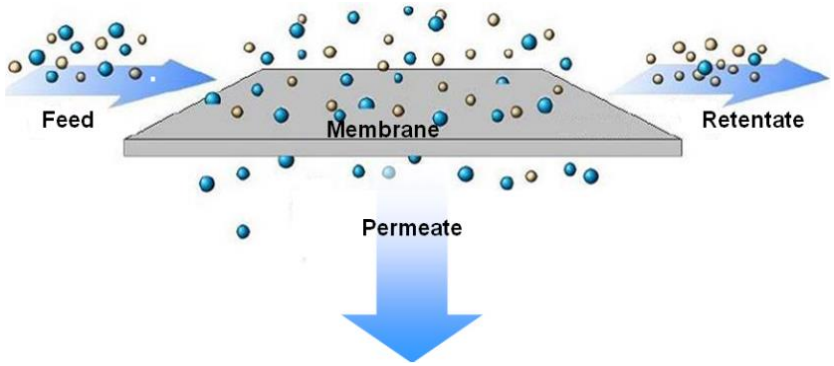
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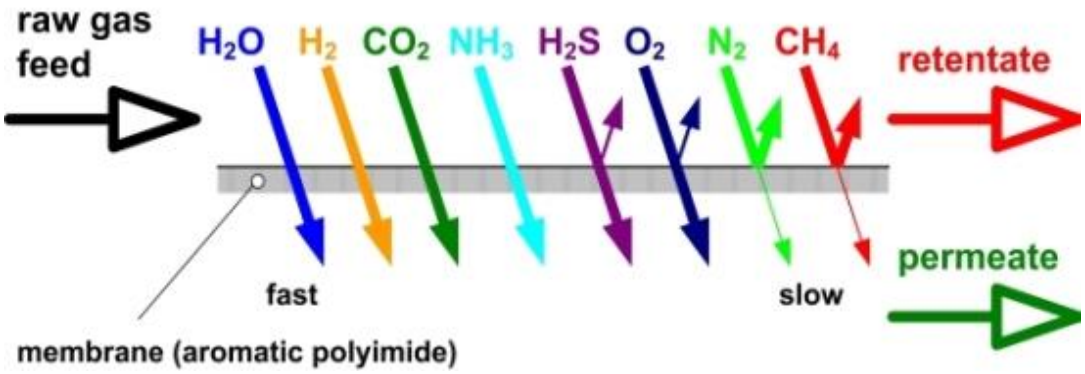
Other Separation Processes – Membranes

Molecules pass through a semi-permeable barrier at different rates

Separation can be based on molecular size, chemical type, …



http://www.elveflow.com/microfluidic-flow-control-products/soft-lithography-products/pdms-membrane-softlithography-station/



http://www.axiom.at/en/gasseparationtechnology

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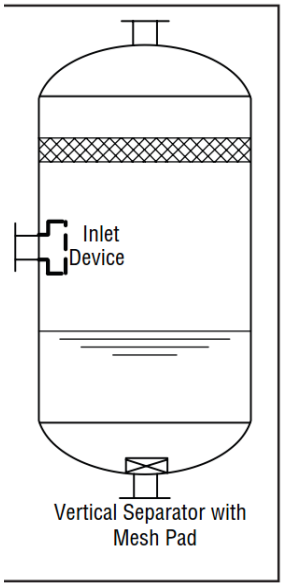
Equipment

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Types of Separators Used in Gas Processing

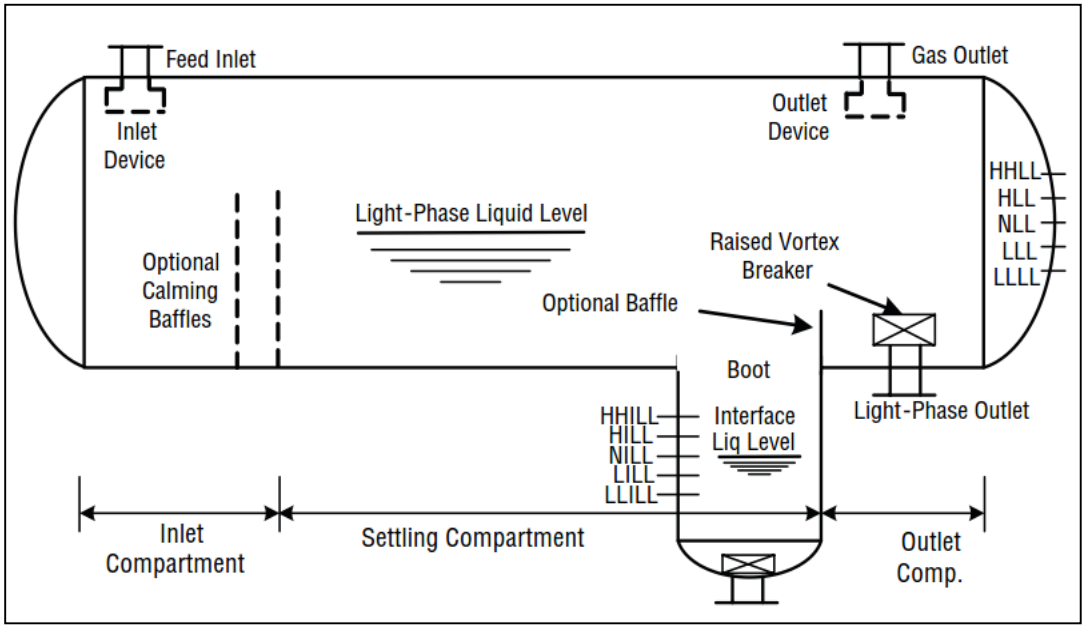
Two-Phase Separators:

- Vapor/Liquid
- Liquid/Liquid
- Vapor/Solid
- Liquid/Solid



Three-Phase Separators:

- Vapor/Liquid/Liquid
- Vapor/Liquid/Solid



Ref: *GPSA Data Book*, 13th ed.

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Separation Considerations

Prioritize key parameters to determine separator selection

- Particle/droplet size to be removed
- Pressure drop
- Turndown ability
- Slug handling requirement
- Fouling service
- Gas or liquid controlled
- Ratio of flowrates for each phase
- Design conditions vs. normal operating conditions vs. upset conditions

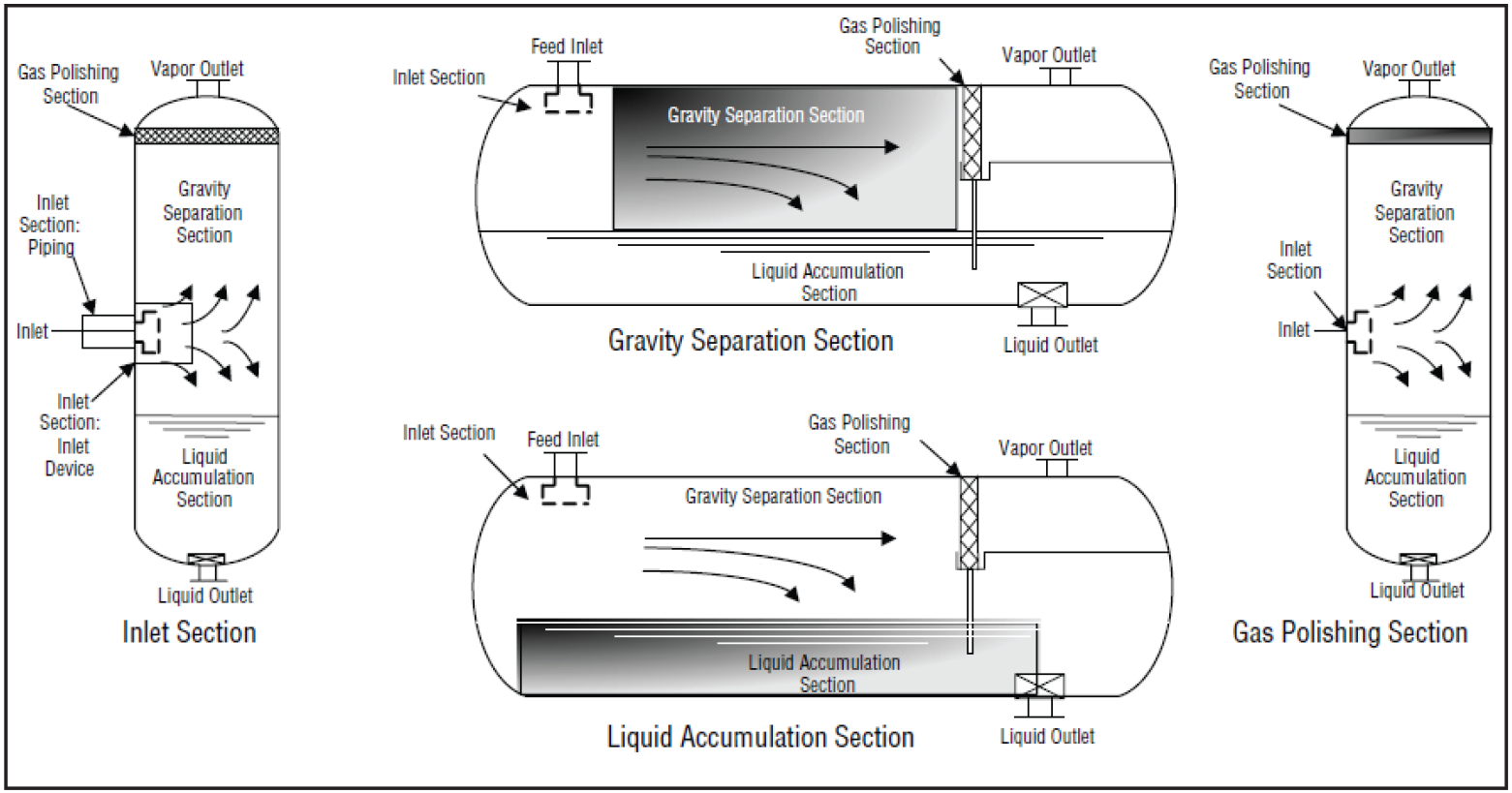
Performance requirements

- Liquid carry-over specification
- Gas carry-under specification
- Water in hydrocarbon specification
- Oil in water specification

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Zones within a separator

FIG. 7-32
Zones of a Gas-Liquid Separator



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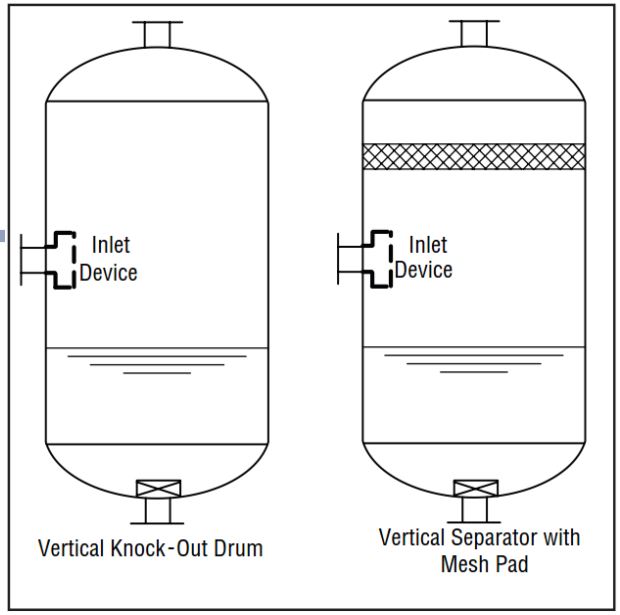
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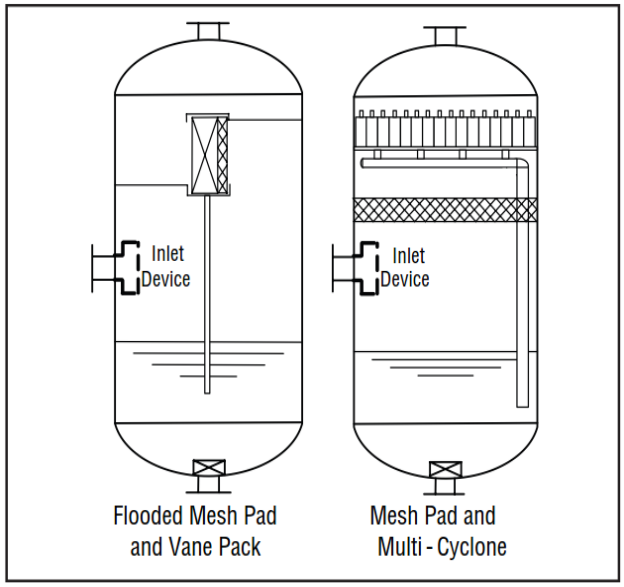
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Vertical Separators

Internals can increase separation efficiency & decreases overall size of vessel

- No internals – bulk separation with no obstructions (e.g., flare knock out drum)
- Mesh pad
- Vane packs
- Cyclones
- Combination internals





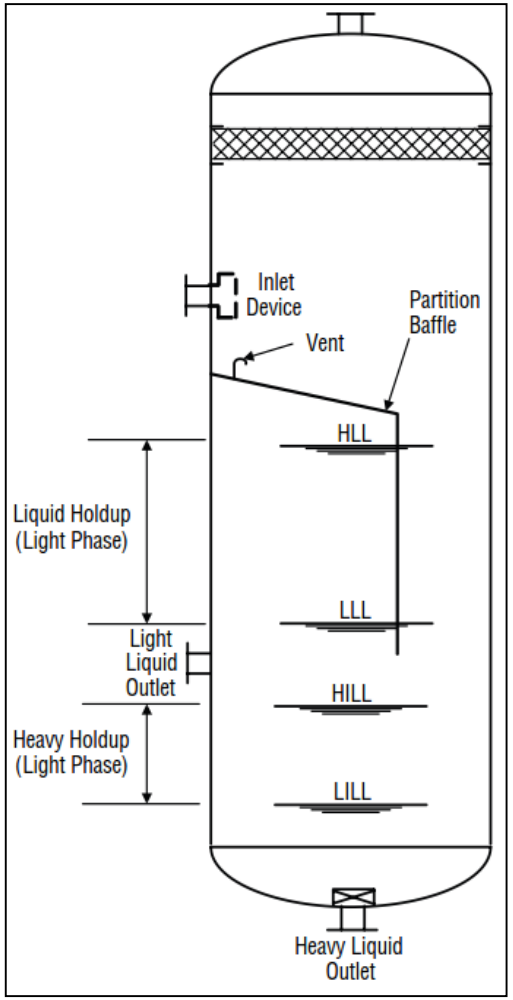
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Vertical Gas-Liquid-Liquid Separators

Can do 3-phase separation in a vertical separator – requires baffling to minimize "whirlpool" effect



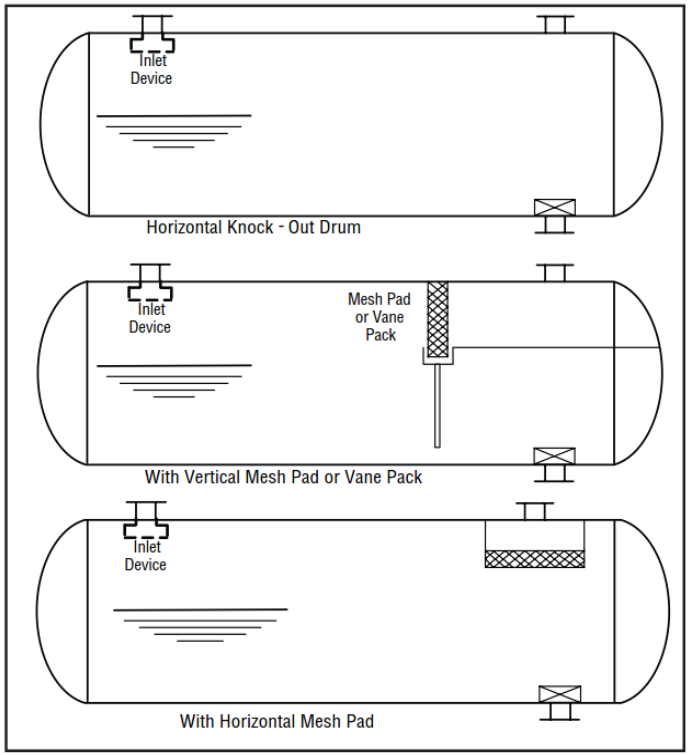
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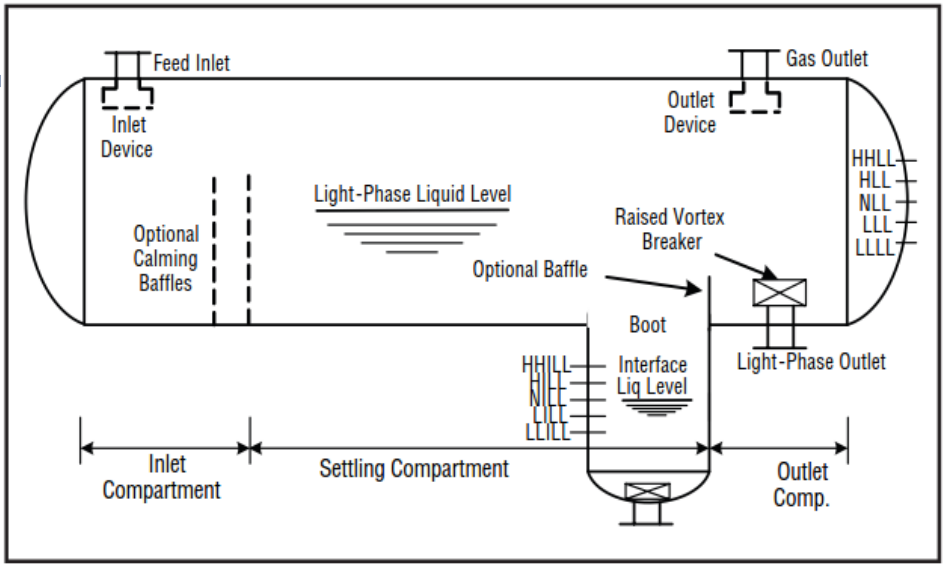
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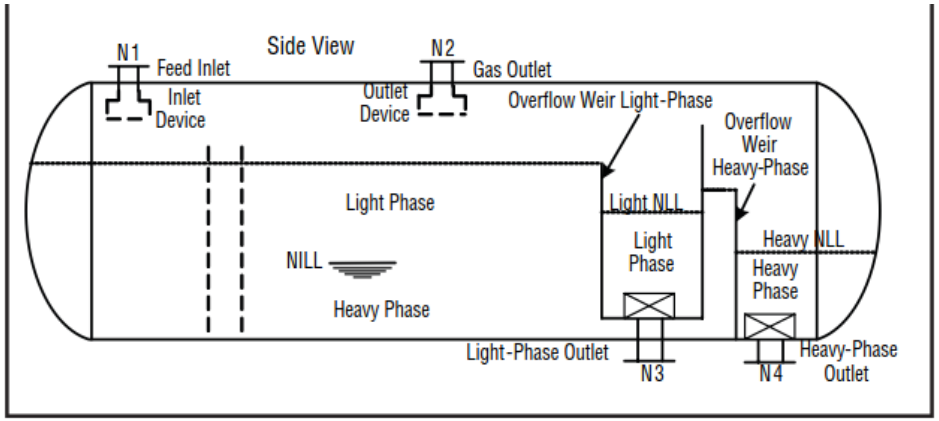
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Horizontal Separators

Like a vertical separator, internals can aid in the separation efficiency & and lead to small vessels.







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Vertical or Horizontal?

FIG. 7-16
Factors that Determine Vessel Orientation

Feature	Vertical	Horizontal
Compact Separators	Yes	Yes
Small Footprint	Yes	—
Small Liquid Surge Drums	Yes	—
Solids Removal with Liquid	Yes	—
Small Capacity Flare K.O. Drums	Yes	—
Gas Dominated Services	Yes	*Yes
Liquid Dominated Services	—	Yes
Three-Phase (G/L/L) Separation	—	Yes
Liquid-Liquid Separation	—	Yes
High Liquid Degassing Residence Time	—	Yes
Pigging & Slug Flow Separation	**Yes	Yes
Foaming Feeds	—	Yes
High Liquid Surge Capacity	—	Yes
Large Capacity Flare K.O. Drums	—	Yes
Solid Removal Through Jetting	—	Yes
High Vapor and Liquid Flow Rates	Yes	Yes

* Some horizontal separators, such as a double barrel type, are also good applications for gas dominated services.
**In some applications where small slugs are possible, slugs can be managed in vertical separators.

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Vertical or Horizontal?

FIG. 7-20
Gas-Liquid-Liquid Separator Selection

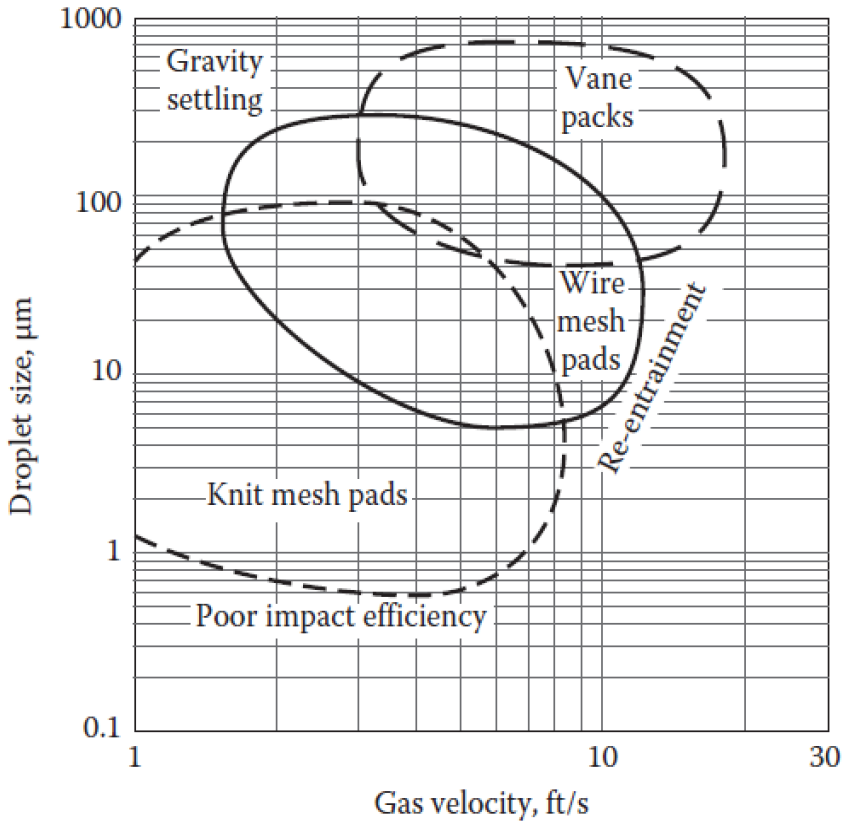
Separator Types	Horizontal No Internals	Horizontal w/Baffle	Horiz./ Vert. w/ Plate Pack or Mesh	Horizontal w/Boot	Horiz. w/ Bucket & Underflow Baffle	Vertical
Liquid-Liquid Separation						
Easy to Settle	Yes	Yes	Yes	Yes	Yes	Yes
Bulk Separation	Yes	Yes		Yes	Yes	Yes
Most Efficient Separation		With coalescer	Yes	With coalescer	With coalescer	With coalescer
Gas-Liquid Separation						
Bulk Separation	Yes	Yes	Yes	Yes	Yes	Yes
Most Efficient Separation	With mist eliminator	With mist eliminator	With mist eliminator	With mist eliminator	With mist eliminator	With mist eliminator
Liquid Controlled (G/L/L)	Yes	Yes	—	Yes	Yes	—
Gas Controlled (G/L/L)	—	—	—	—	—	Yes
Fouling Service	Yes	Yes	—	Yes	Yes	Yes
Solids Handling	Yes	—	—	—	—	Yes
Interface Level Control not Required	—	—	—	—	Yes	—
Low Light Phase (Oil) Flow Rate	—	—	—	—	Yes	—
Low Water Phase Flow Rate	—	—	—	Yes	—	—

Ref: *GPSA Data Book*, 14th ed.

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Mist Extraction

Internals chosen based on gas flow & droplet size.



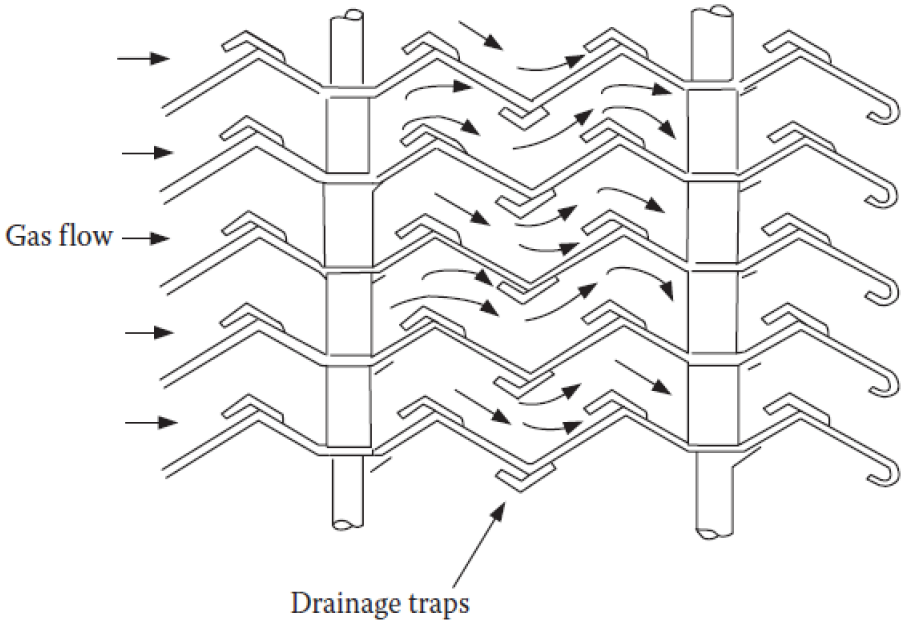


Fig. 5.2 Vane Pack
Fundamentals of Natural Gas Processing, 2nd ed.
Kidnay, Parrish, & McCartney

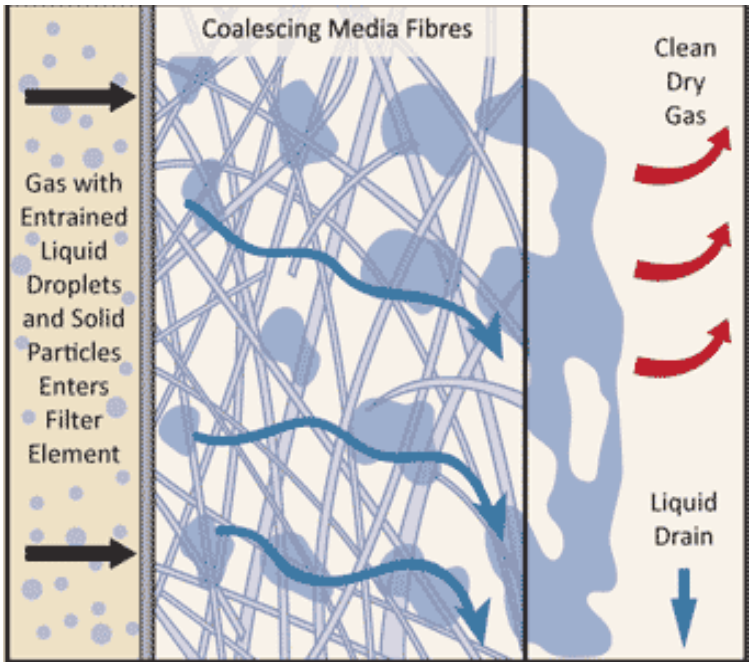
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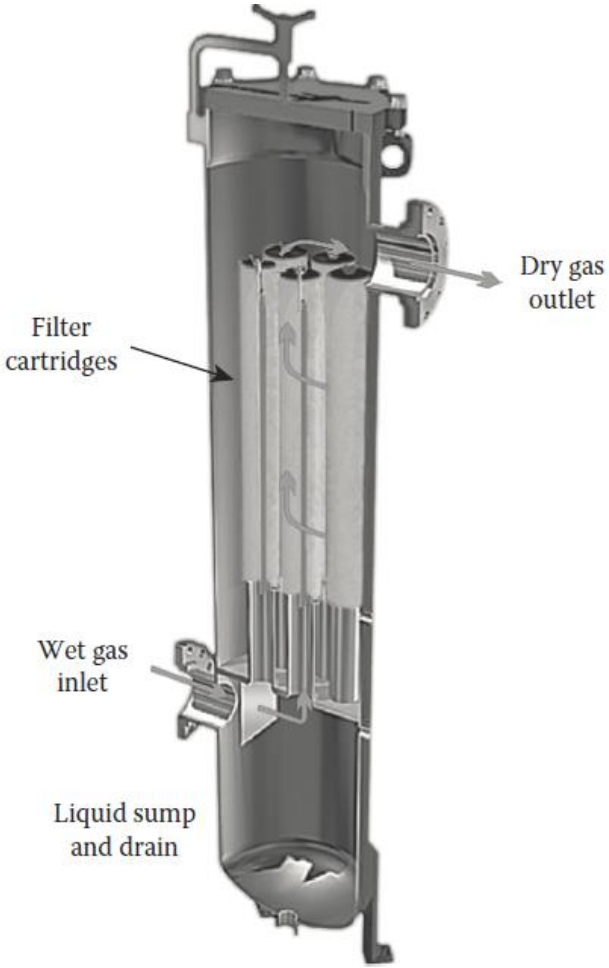
Coalescing filters

Remove very fine liquid particles (less then 3 μm)

Coalescers have media that allow the very small particles to combine & the drain via gravity



http://www.kelburneng.co.uk/gas-filtration.php



Fundamentals of Natural Gas Processing, 2nd ed.
Kidnay, Parrish, & McCartney

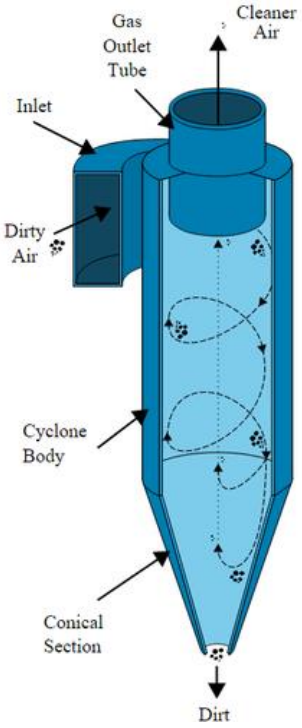
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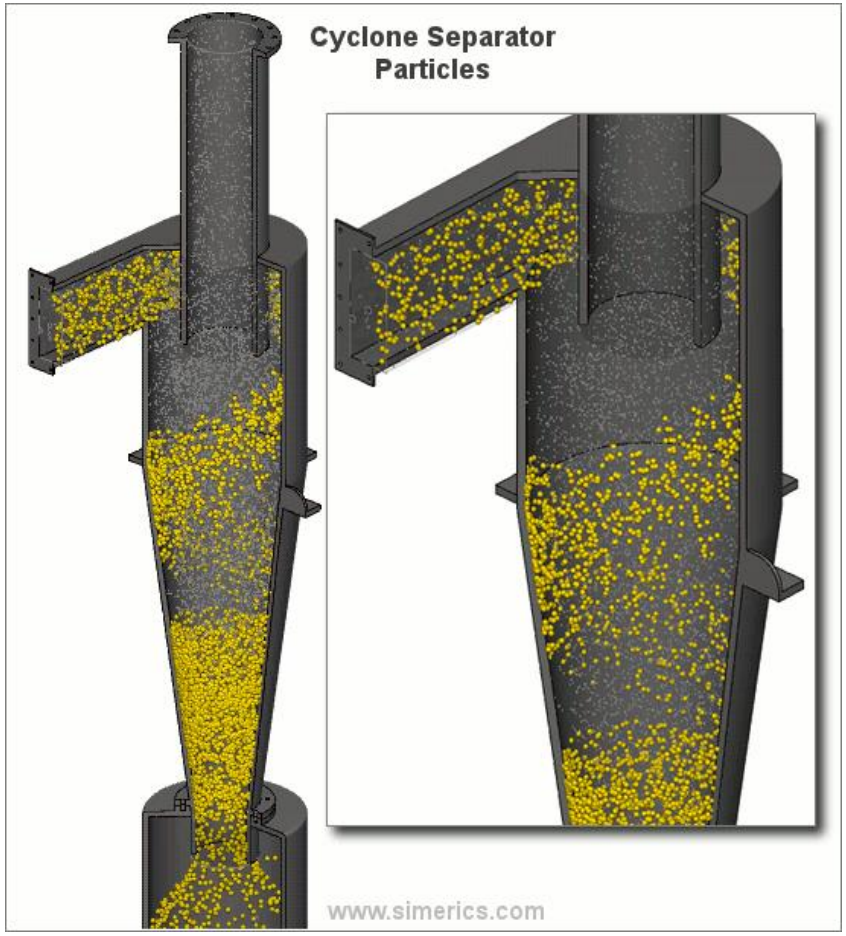
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Separation by centrifugal force

Vortex flow. Heavier particles hit outside walls & fall downward

Can be used to separate liquids and/or solids from gas flow





http://energyeducation.ca/encyclopedia/Cyclone_separator

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Sizing of Vertical Separators

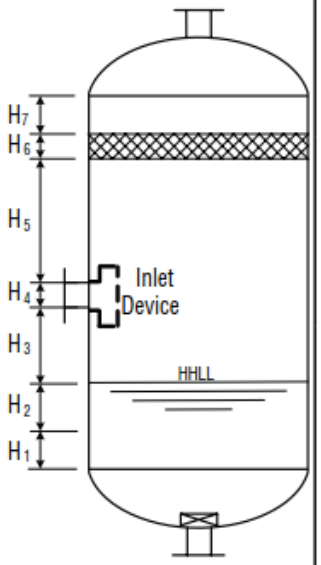
When gas flowrate controls sizing:

- Diameter is based on allowable velocity through internal (mesh pad, vane, etc.)
- Height is based on liquid volume requirements and physical height requirements of internals

When liquid flowrate controls sizing:

- Liquid dictates volume requirements
- Height and diameter based on most economic ratio (i.e. L:D of 3)

Dim	Section	Distance
H_1	Bottom Tangent to LLLL	12-18 in, can be lower depending on instrument mount
H_2	LLLL to HHLL	Per required surge time or retention time
H_3	HHLL to Feed Nozzle Bottom	1 ft - 2 ft for diffuser 0.25 D for all other inlet devices, with 2 ft minimum
H_4	Nozzle Diameter	Larger of piping size or velocity head criteria
H_5	Nozzle Top to Mist Eliminator Bottom	1 ft to 3 ft for diffuser 0.5D for all other inlet devices
H_6	Mist Eliminator	4 in to 6 in typical
H_7	Mist Eliminator to Top Tangent	6 in minimum or per Fig. 7-38



Ref: *GPSA Data Book*, 13th ed.

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Typical Surge & Retention Times

Service	Control Surge Time, LLL to HLL	Retention Time, Empty to NLL
Compressor Drum	2 minutes	
Flash Drum	2 – 5 minutes	
Reflux Drum	5 minutes on product plus reflux	
Surge Drum Upstream of Tower	5 – 10 minutes	
Surge Drum Upstream of Fired Heater	10 minutes	
Tower Sump	Depends on Tower type	
Net Product to Storage	5 minutes	
Amine Flash Drum		5 – 10 minutes
Glycol Flash Drum		10 – 20 minutes
Cold Separator (Gas/NGL/EG)		15 – 30 minutes
Refrigeration Accumulator	5 minutes or based on system requirements	
Refrigeration Economizer	3 minutes	
Heat Medium Surge Drum	Max liquid expansion based on 25% - 75% full	

Ref: Fig. 7-42 *GPSA Data Book*, 14th ed.

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Fractionators: Typical Parameters

FIG. 19-19

Typical Fractionator Parameters

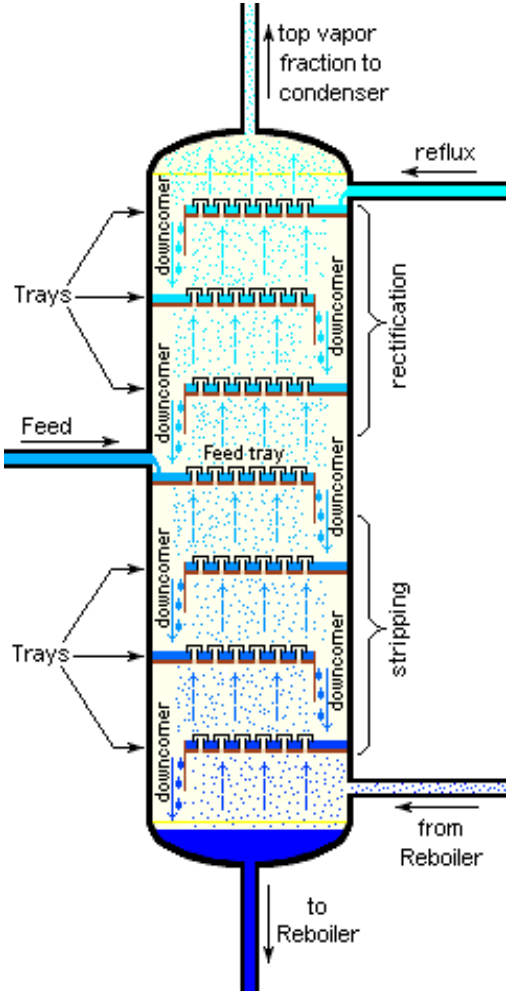
	Operating Pressure, psig	Number of Actual Trays	Reflux[1] Ratio	Reflux[2] Ratio	Tray Efficiency, %
Demethanizer	200 – 400	18 – 26	Top Feed	Top Feed	45 – 60
Deethanizer	375 – 450	25 – 35	0.9 – 2.0	0.6 – 1.0	60 – 75
Depropanizer	240 – 270	30 – 40	1.8 – 3.5	0.9 – 1.1	80 – 90
Debutanizer	70 – 90	25 – 35	1.2 – 1.5	0.8 – 0.9	85 – 95
Butane Splitter	80 – 100	60 – 80	6.0 – 14.0	3.0 – 3.5	90 – 100
Rich Oil Fractionator (Still)	130 – 160	20 – 30	1.75 – 2.0	0.35 – 0.40	Top 67 Bottom 50
Rich Oil Deethanizer	200 – 250	40	–	–	Top 25 – 40 Bottom 40 – 60
Condensate Stabilizer	100 – 400	16 – 24	Top Feed	Top Feed	50 – 75

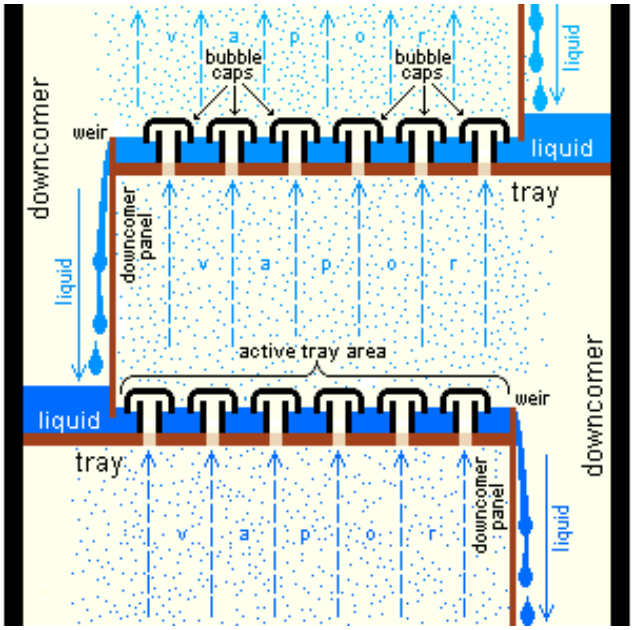
[1]Reflux ratio relative to overhead product, mol/mol
[2]Reflux ratio relative to feed, gal./gal.

Ref: *GPSA Data Book*, 13th ed.

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Fractionation Columns & Trays





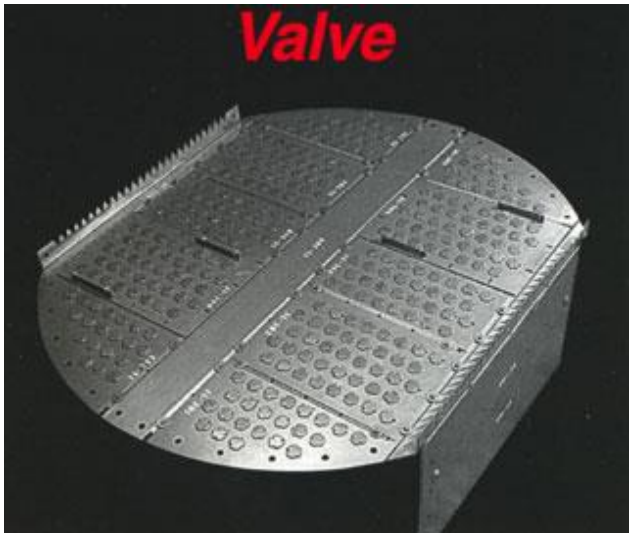
Drawings by Henry Padleckas
http://en.wikipedia.org/wiki/Fractionating_column

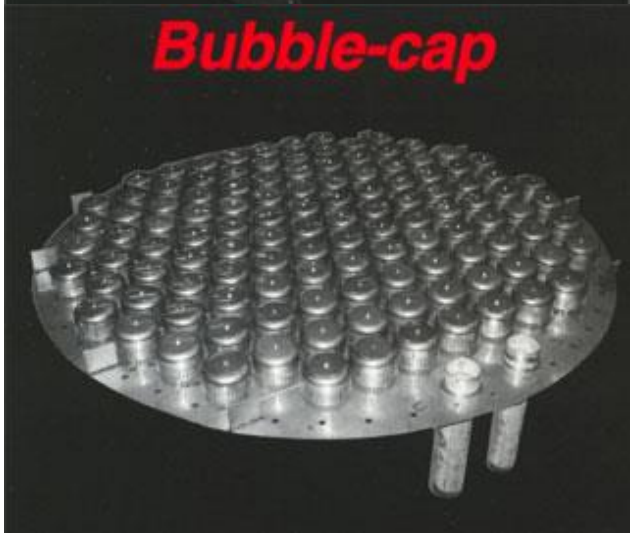
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Fractionation Tray Types







http://www.termoconsult.com/empresas/acs/fractionation_trays.htm

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Trays & Packing

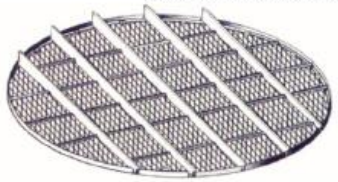

VALVE TRAY


ADV™ VALVE S-VALVE


BUBBLE-CAP TRAY


S-RING
SR+ RING SMTP


STRUCTURED PACKING


BED LIMITER


DISTRIBUTOR

http://www.ec21.com/product-details/Tower-Internals--3942077.html

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Packed towers

Liquid & vapor flow countercurrent through packing

- No specific “tray” or number of “trays”
- A mass transfer zone or “transfer unit” consists of a quantity of packing

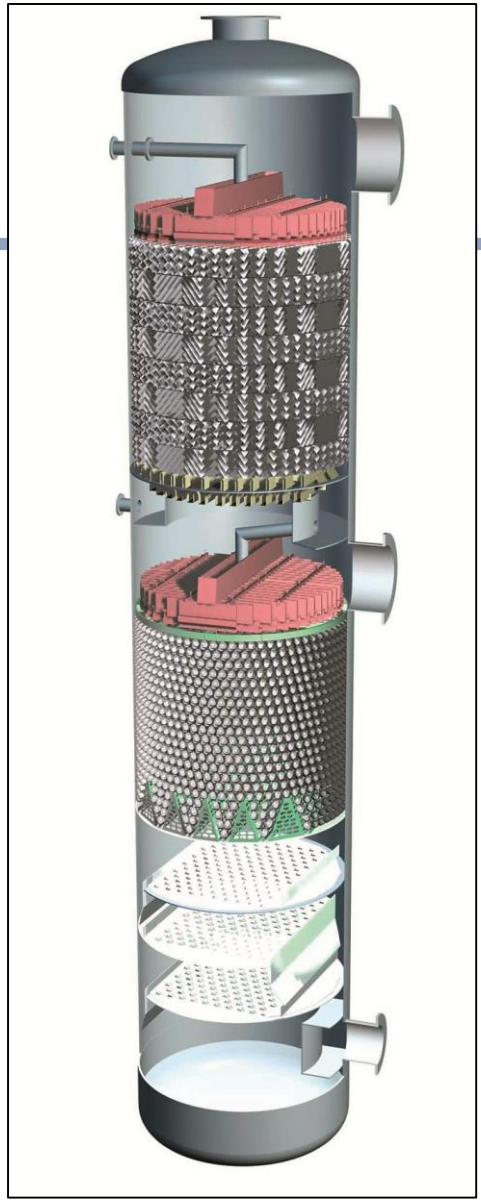
Types:

- Random packing
- Structured packing
- Grids

Sizing of tower (diameter) is based on

- Jet flooding (combination of vapor/liquid limit)
- Pressure drop limit (indicates excessive loading)

Typically smaller diameter than trays



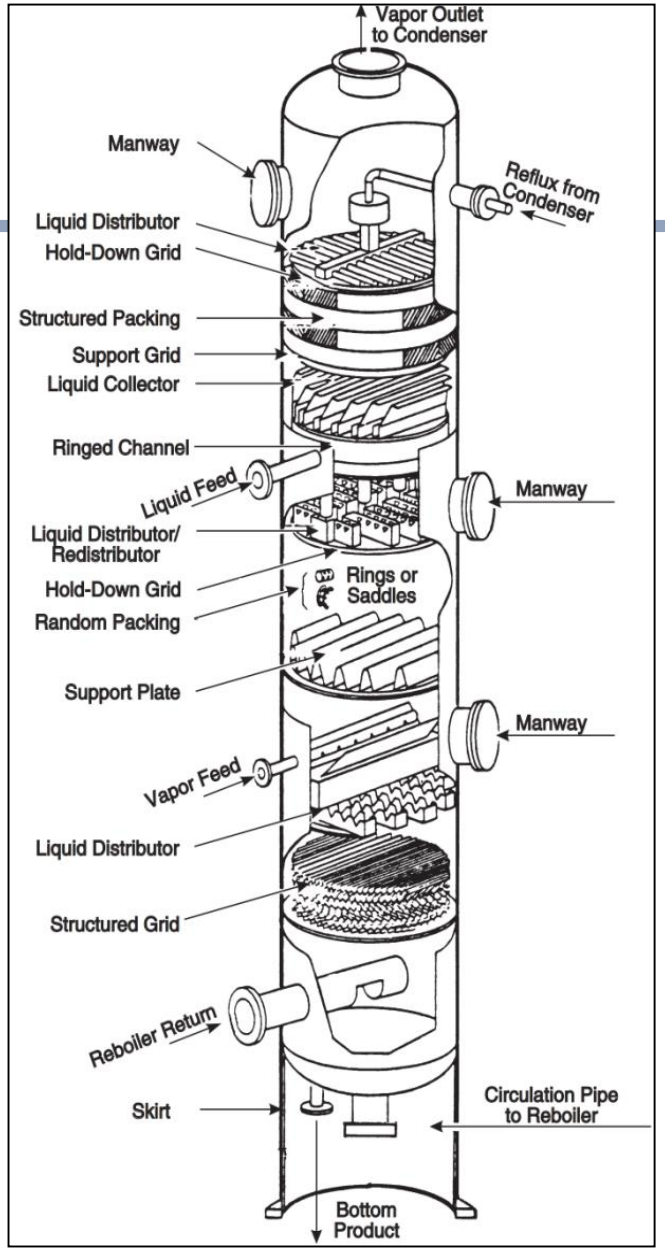
http://www.sulzer.com/mr/Products-and-Services/Separation-Technology/Distillation-and-Absorption/Distillation

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Tower Height Calculation

Height based on:

- Number of trays, tray spacing
- Number of packed beds, bed height
- Nozzles and feed internals
- Sump height
- Vapor disengagement
- Manways
- Other internals
  - Chimney trays
  - Bed limiters
  - Redistributors



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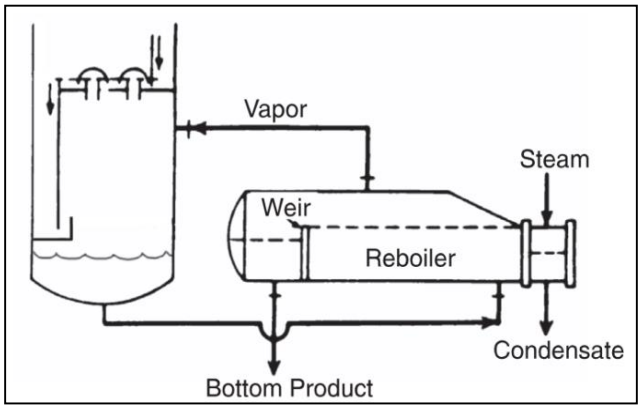
Reboiler considerations

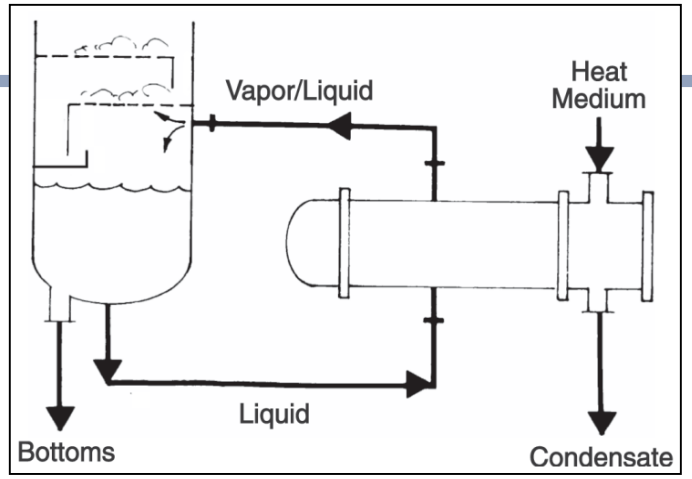
Hydraulics

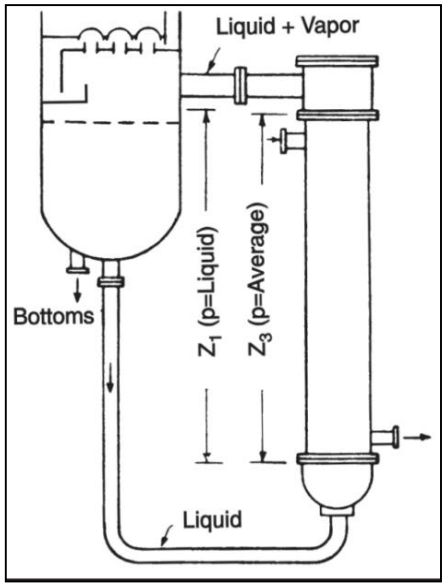
- Forced circulation
- Natural circulation – most typical

Configuration

- Once through
  - Treat as a stage of separation
- Recirculation







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Absorption & Stripping

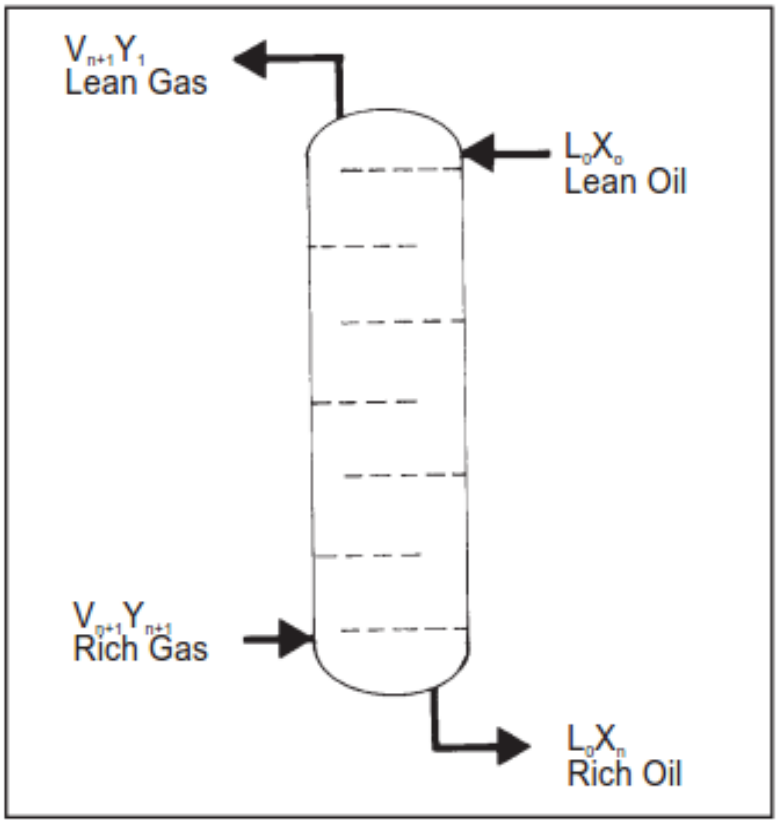
Absorbers: desired component in feed gas

- Absorb a gas phase component (solute) into a liquid (solvent)
- Amine, Selexol, glycol dehydration, etc.

Strippers: desired component in feed liquid

- Strip a dissolved component from liquid into the gas phase
- Sour water, glycol regeneration (stripping gas), etc.

FIG. 19-50
Absorption Nomenclature



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Adsorption – Mole Sieve Dehydration

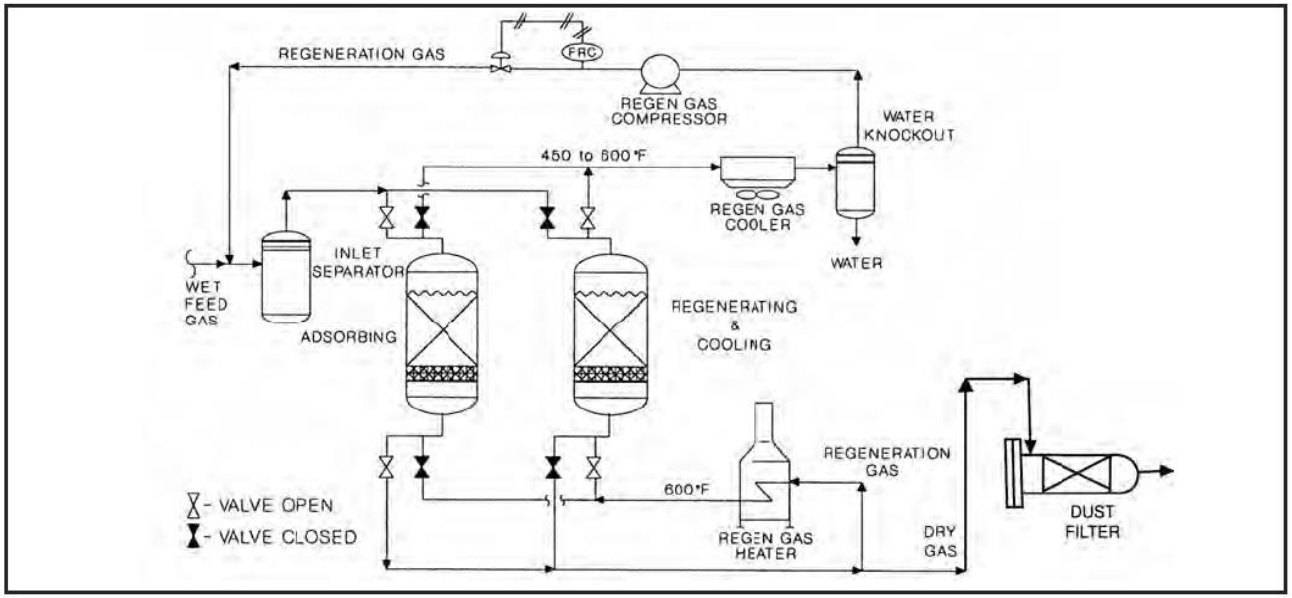
Typically fixed beds with at least two vessels – on in adsorption & one in desorption

Forms of desorption

- TSA – Temperature Swing Adsorption
- PSA – Pressure Swing Adsorption

FIG. 20-76

Example Solid Desiccant Dehydrator Twin Tower System



Ref: *GPSA Data Book*, 13th ed.

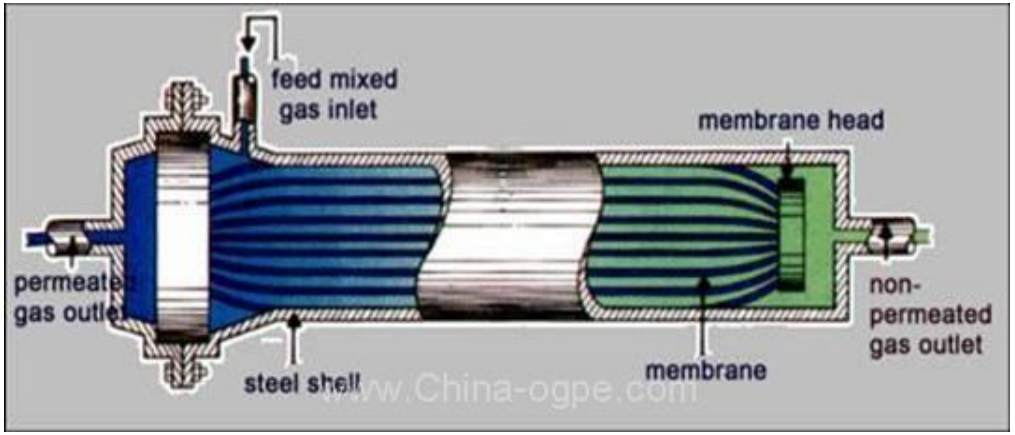
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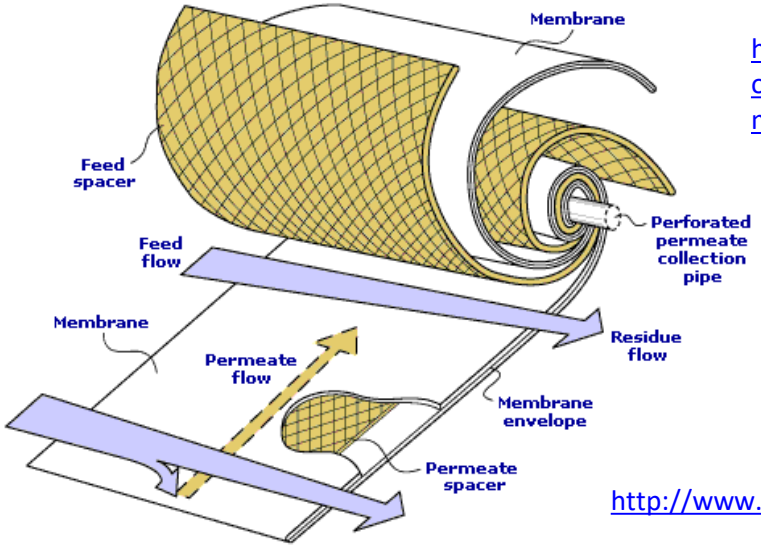
Membrane separation

Typical vessel configurations

- Rolled membrane
- Hollow fiber



http://www.china-ogpe.com/showroom/277/html/product_Gas_Separation_By_Membrane_9_4832.html



http://www.mtrinc.com/faq.html

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Summary

Separation of components based on phase equilibrium in separators & fractionators

- Material balance calculation based on a “flash” calculation
- Can further control with adsorbents & membranes

Vessels sized to get the physical separation between vapor & liquid phases

- Internals can greatly increase the separation efficiency leading to smaller vessels

Fractionators can be thought of as cascaded contactors & separators

- Internals may consist of trays and/or packing

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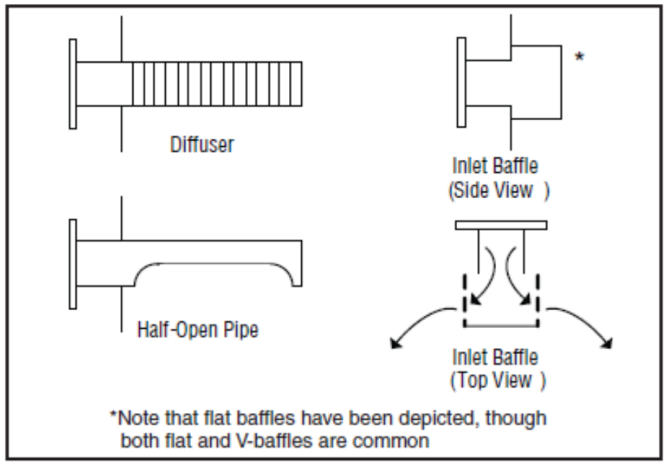
Supplemental Slides

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Inlet devices

FIG. 7-34
Common Vertical Vessel Inlet Devices



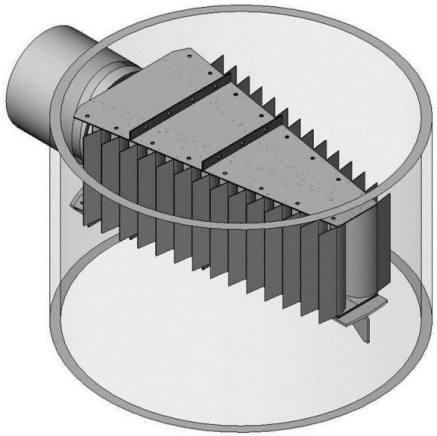
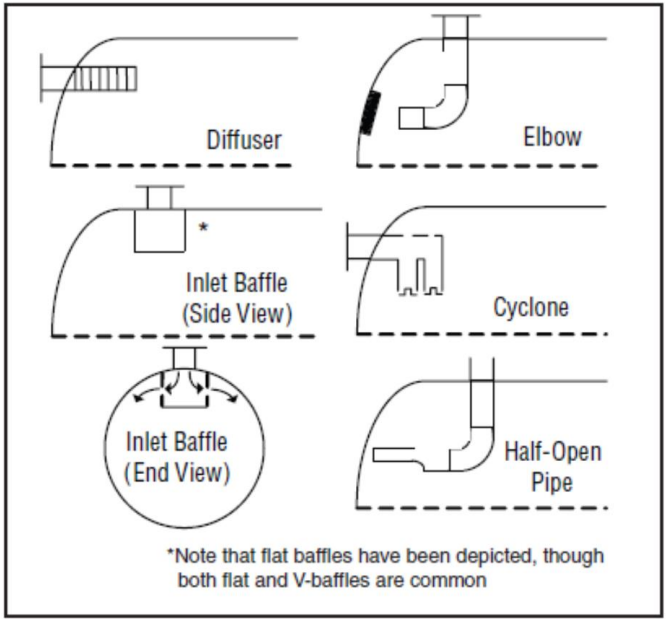


FIG. 7-35
Common Horizontal Vessel Inlet Devices



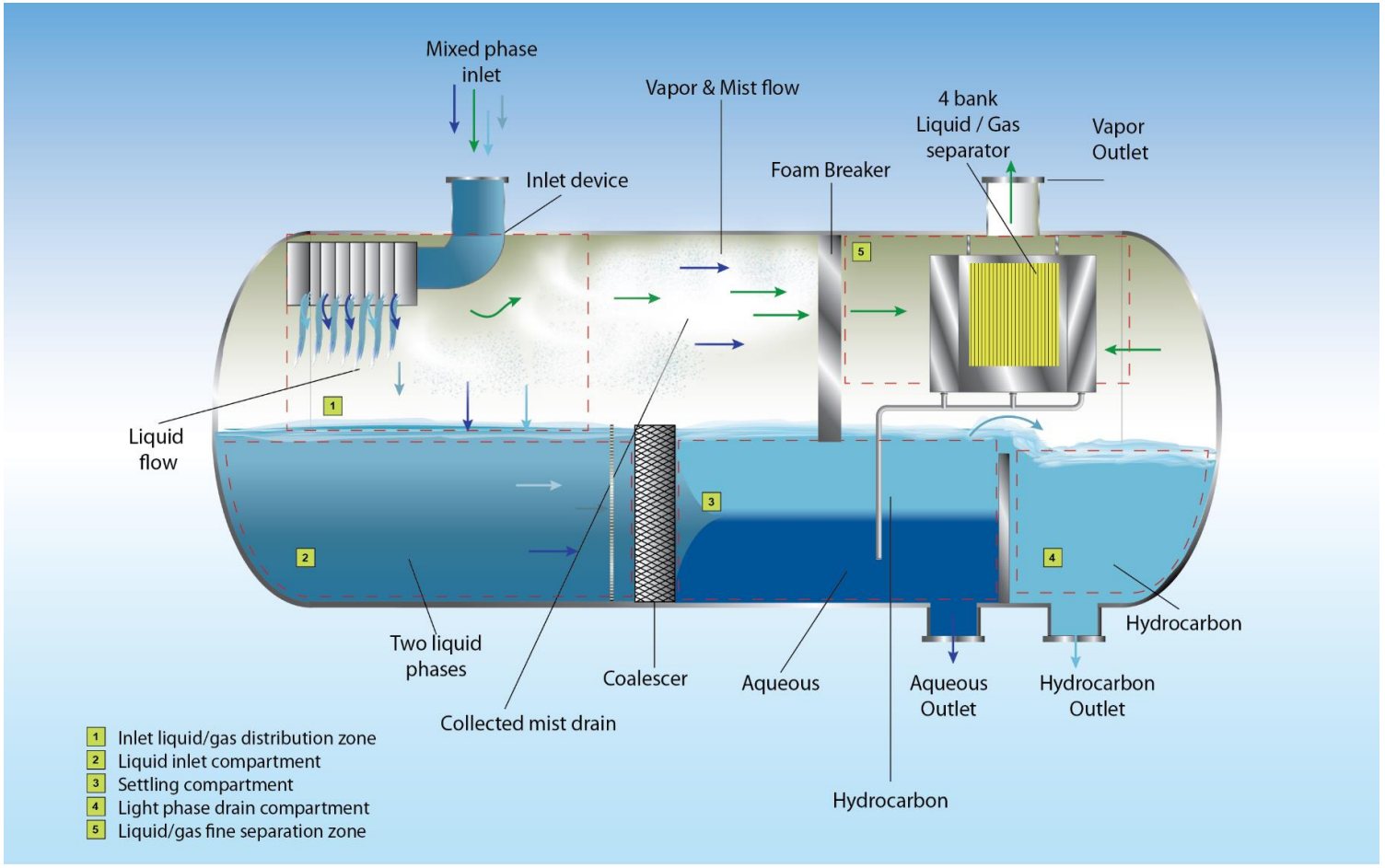
Figures *GPSA Data Book*, 14th ed.

Shell Schoepentoeter™
http://www.sulzer.com/ro/Products-and-Services/Separation-Technology/Feed-Inlet-Devices/Shell-Schoepentoeter-and-Schoepentoeter-Plus

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Separator Zones



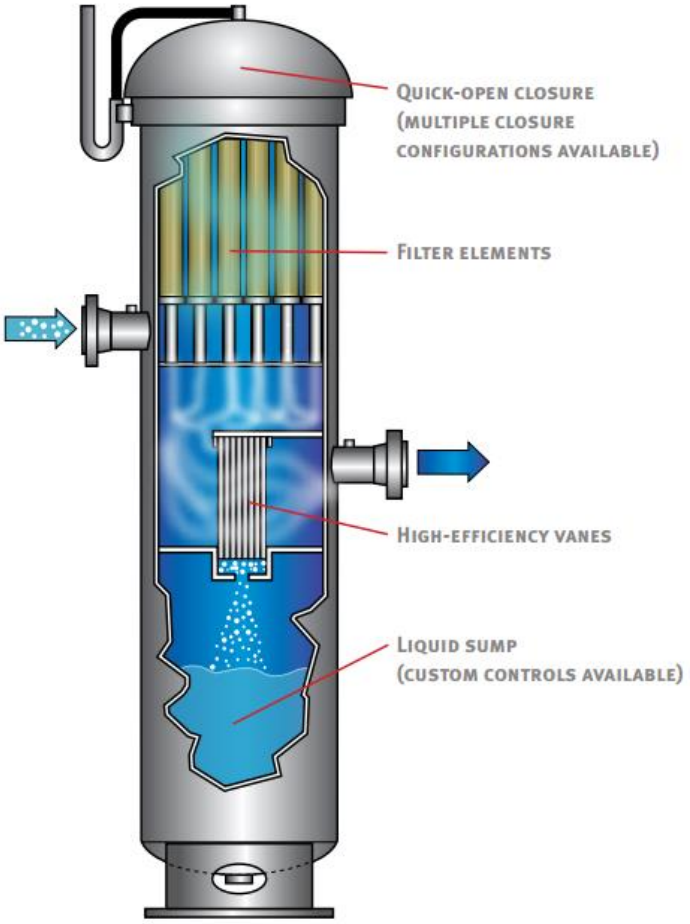
http://petroleumebook.com/separator-ebook-collection-about-separator.html

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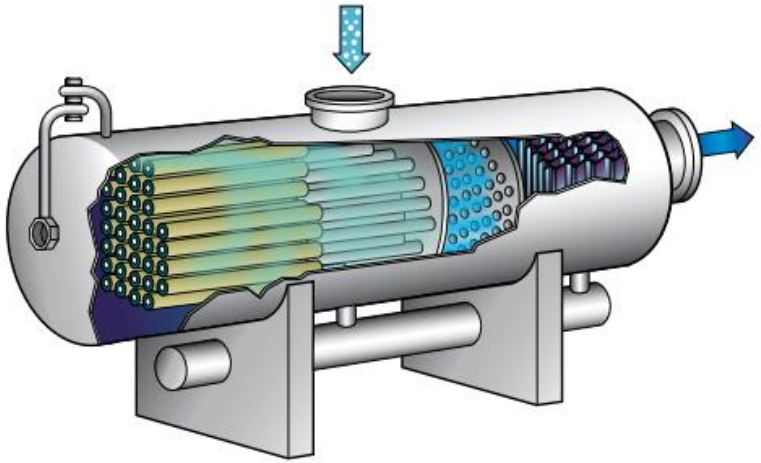
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Filter Separators



VERTICAL FILTER-SEPARATOR

FOR APPLICATIONS WHERE SPACE IS LIMITED.



HORIZONTAL FILTER-SEPARATOR

FOR APPLICATIONS REQUIRING HIGH LIQUID STORAGE. VERTICAL AND HORIZONTAL SUMPS AVAILABLE.

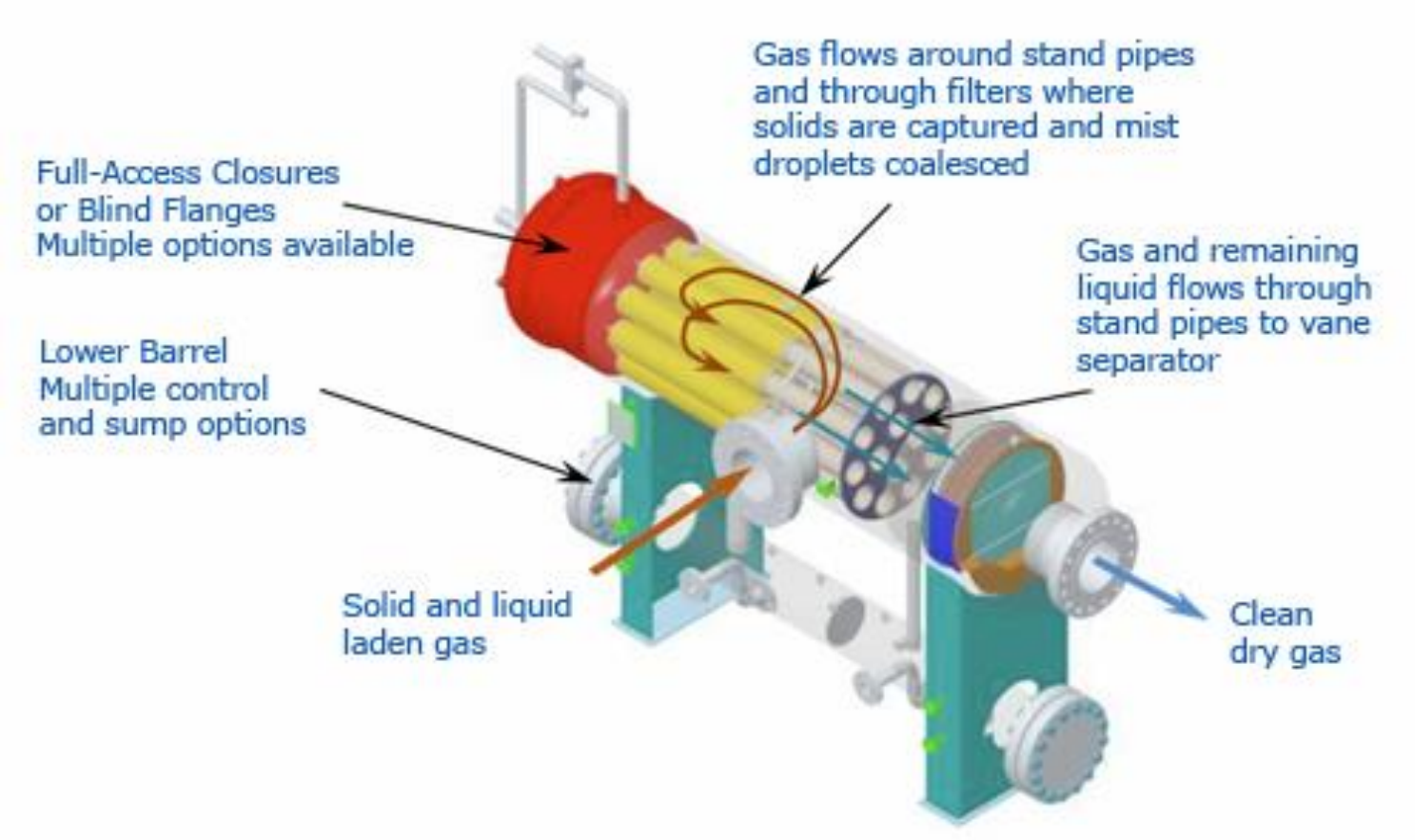
http://cdn2.hubspot.net/hubfs/2041813/Brochure_PDFs/Filter-Separator_brochure.pdf?hsCtaTracking=c1b7a92d-bf53-47b8-92c6-ca06c50058ec%7C1651fd38-b4ac-4e94-9a5c-4825cef0e900&__hstc=6098668.694ff329e9e46f2ca61b78dfda4d809e.1486868568715.1486868568715.1486868568715.1&__hssc=6098668.11.1486868568715&__hsfp=3776107698

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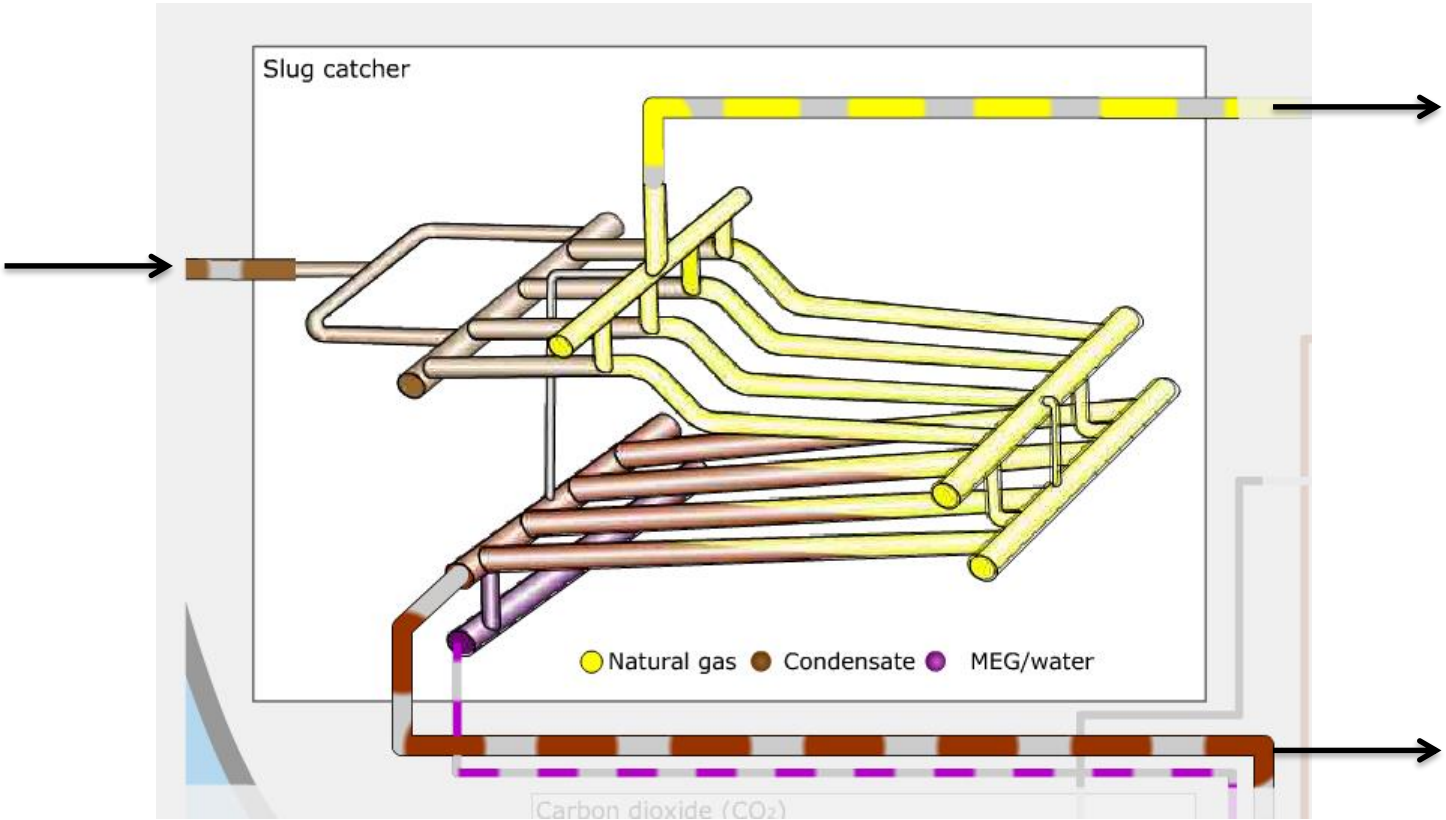
Filter Separators



http://bartlettcontrols.com/wp1/wp-content/uploads/2013/12/fs1_LG.png

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Harp Design Slug Catcher



Ref: http://www.statoil.com/en/OurOperations/pipelines/Documents/veien_til_lng_engelsk_enkel.swf

Additional video: https://www.youtube.com/watch?v=f1bIUm2Op3U

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