PROCESS EQUIPMENT DESIGN COURSE

SEPARATORS

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Session Overview

- Introduction & Theory
- Separator Design & Construction
- Gas-Liquid Separator Design
- Gas-Liquid-Liquid Separator Design
- Mechanical Design
- Standards & References
- Exercises

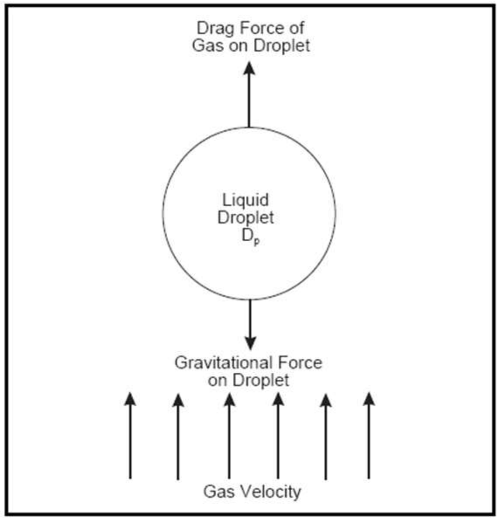
Introduction & Theory

- Three principles used to achieve physical separation of gas and liquids or solids : *momentum*, *gravity settling*, and *coalescing*.

- Separator : a pressure vessel designed to divide a combined liquid–gas system into individual components that are relatively free of each other for subsequent disposition or processing.

- Gravity Settling :

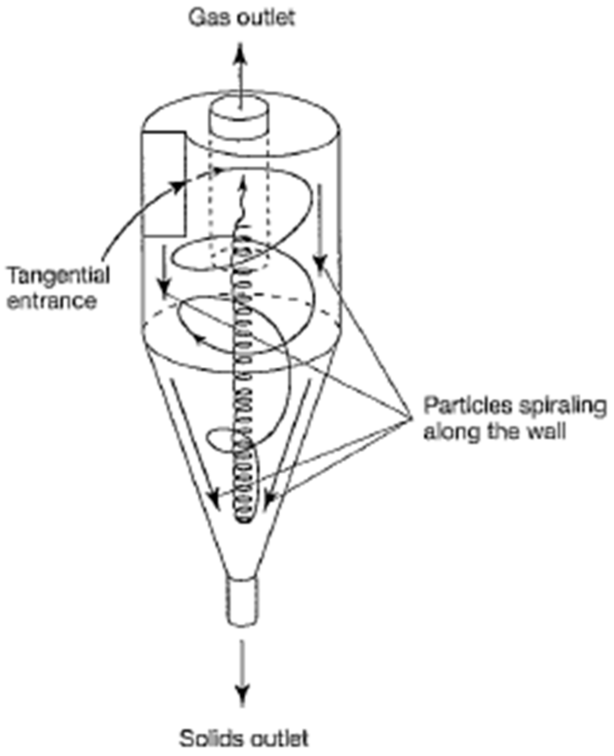
  Liquid droplets will settle out of a gas phase if the gravitational force acting on the droplet is greater than the drag force of the gas flowing around the droplet.



Introduction & Theory

- Momentum:

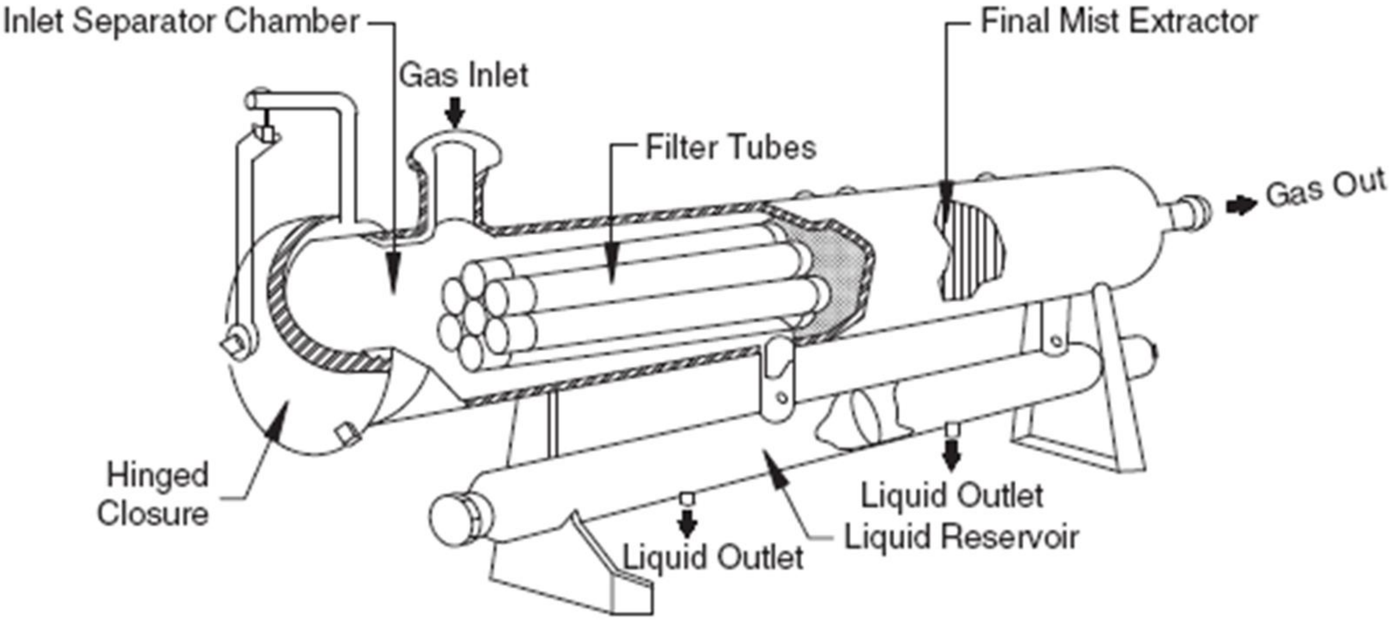
  Fluid phases with different densities will have different momentum. If a two phase stream changes direction sharply, greater momentum will not allow the particles of heavier phase to turn as rapidly as the lighter fluid, so separation occurs.



Introduction & Theory

- Coalescing:

  These are used in applications where conventional separators employing gravitational or centrifugal force are ineffective.

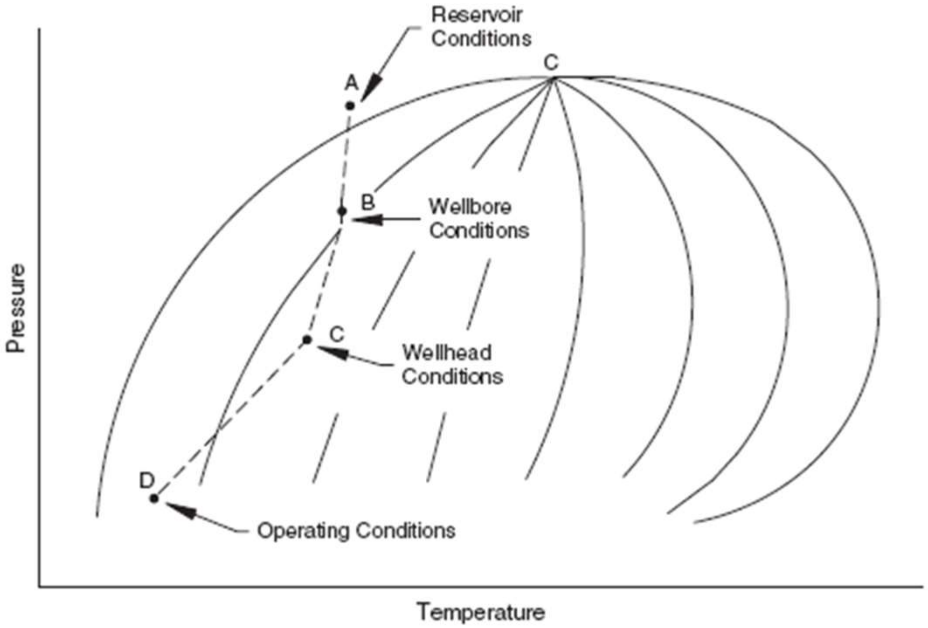


Introduction & Theory

WHY Separation is needed ?

- Downstream equipment cannot handle gas–liquid mixtures, for example:
  - Pumps require gas-free liquid;
  - Compressor and dehydration equipment require liquid-free gas;
  - Product specification set limits on impurities
  - Measurement devices for gases or liquids are highly inaccurate when another phase is present.

- Phase behavior :



Introduction & Theory

- The following factors must be determined before separator design:
  - gas and liquid flow rates (minimum, average, and peak),
  - operating and design pressures and temperatures,
  - surging or slugging tendencies of the feed streams,
  - physical properties of the fluids such as density, viscosity and compressibility factor,
  - designed degree of separation (e.g., removing 100% of particles greater than 10 mm),
  - presence of impurities (paraffin, sand, scale, etc.),
  - foaming tendencies of the crude oil, and
  - corrosive tendencies of the liquids or gas.

Introduction & Theory

- Gravity Settling:

$$V_t = \sqrt{\frac{2\,g\,M_p\,(\rho_l - \rho_g)}{\rho_l\,\rho_g\,A_p\,C'}} = \sqrt{\frac{4\,g\,D_p\,(\rho_l - \rho_g)}{3\,\rho_g\,C'}}$$

V_t = critical or terminal gas velocity necessary for particles of size D_p to drop or settle out of gas, m/s
M_p = mass of droplet or particle, kg
ρ_g = gas phase density, kg/m^3
ρ_l = liquid phase density, droplet or particle, kg/m^3
A_p = particle or droplet cross sectional area, m^2
C' = drag coefficient of particle, dimensionless
μ = viscosity of continuous phase, mPa • s

$$Re = \frac{1{,}000\,D_p\,V_t\,\rho_g}{\mu}$$

Introduction & Theory

- Gravity Settling:

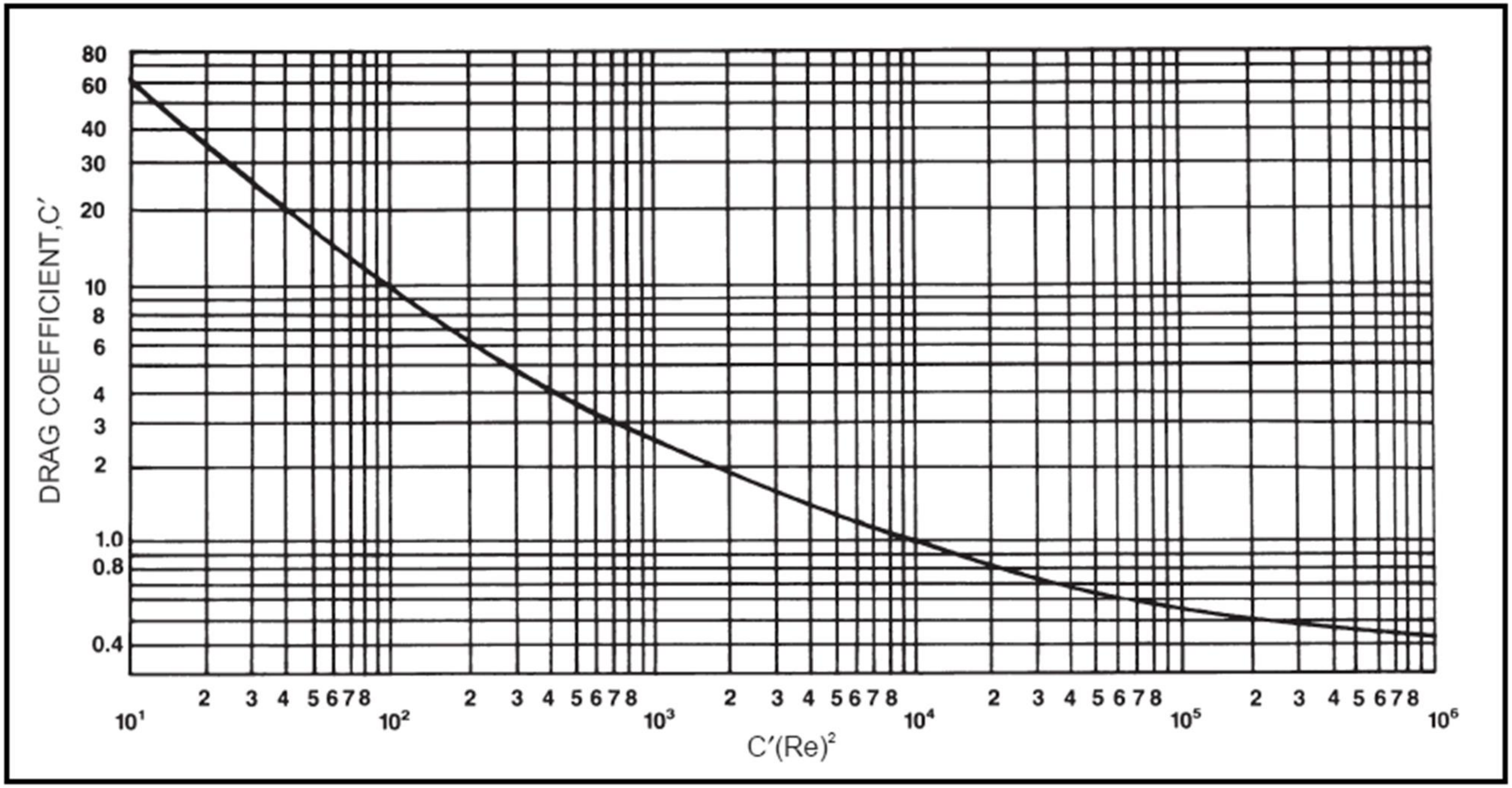
SI :

$$C'(Re)^2 = \frac{(1.31)(10^7)\rho_g D_p^3(\rho_l - \rho_g)}{\mu^2}$$

FPS :

$$C'(Re)^2 = \frac{(0.95)(10^8)\rho_g D_p^3(\rho_l - \rho_g)}{\mu^2}$$

Drag Coefficient of Rigid Spheres[15]



Introduction & Theory

- Gravity Settling:

  Stoke's Law

  At low Reynolds numbers (less than 2), a linear relationship exists between the drag coefficient and the Reynolds number (corresponding to laminar flow). Stoke's Law applies in this case can be expressed as:

$$V_t = \frac{1{,}488\, g\, D_p^2\, (\rho_l - \rho_g)}{18\, \mu}$$

- The droplet diameter corresponding to a Reynolds number of 2 can be found using a value of 0.025 for KCR in:

$$D_p = K_{CR}\left[\frac{\mu^2}{g\, \rho_g\, (\rho_l - \rho_g)}\right]^{0.33}$$

- Stoke's law is typically applicable for small droplet sizes and/or relatively high viscosity liquid phases.

Introduction & Theory

- Gravity Settling:

  Intermediate Law

  For Reynold's numbers between 2 and 500, the Intermediate Law applies, and the terminal settling law can be expressed as:

$$V_t = \frac{3.49\, g^{0.71}\, D_p^{1.14}\, (\rho_l - \rho_g)^{0.71}}{\rho_g^{0.29}\, \mu^{0.43}}$$

- The droplet diameter corresponding to a Reynolds number of 500 can be found using a value of 0.334 for KCR in:

$$D_p = K_{CR} \left[\frac{\mu^2}{g\, \rho_g\, (\rho_l - \rho_g)} \right]^{0.33}$$

- The intermediate law is usually valid for many of the gas liquid and liquid-liquid droplet settling applications encountered in the gas business.

Introduction & Theory

- Gravity Settling:

  Newton’s Law

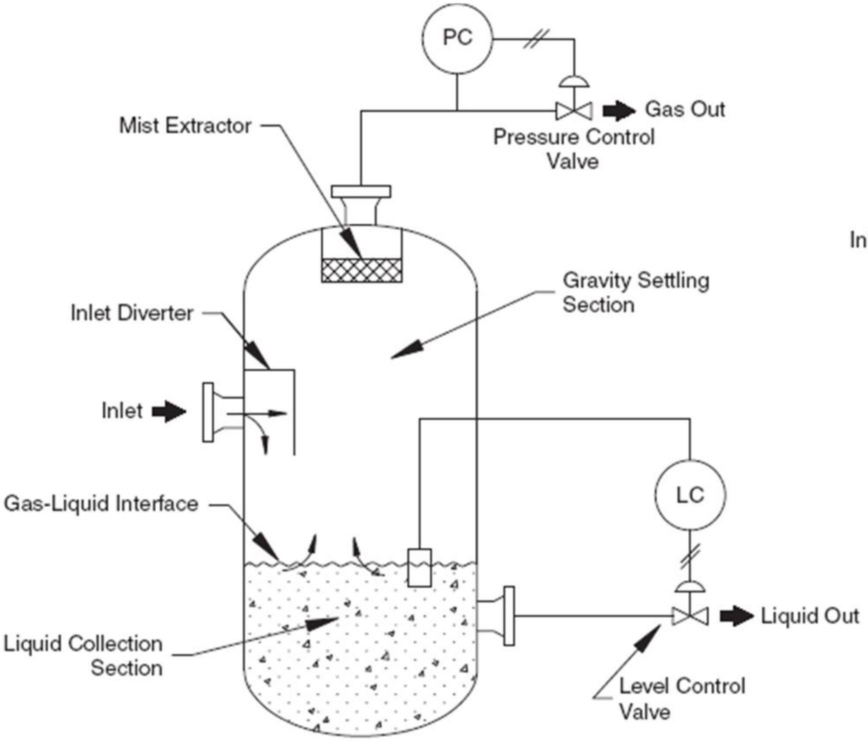
  Newton’s Law is applicable for a Reynold’s number range of approximately 500 – 200,000, and finds applicability mainly for separation of large droplets or particles from a gas phase, e.g. flare knockout drum sizing. The limiting drag coefficient is approximately 0.44 at Reynolds numbers above about 500.

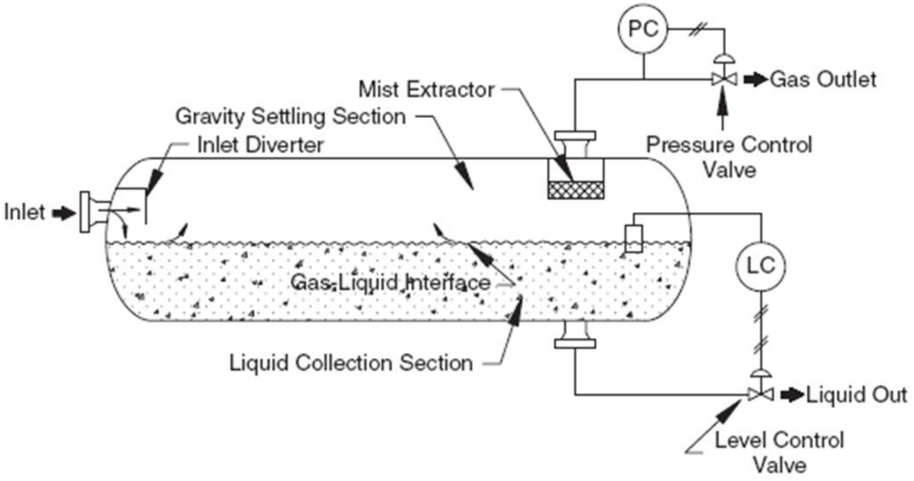
$$V_t = 1.74\sqrt{\frac{g\,D_p\,(\rho_l - \rho_g)}{\rho_g}}$$

- An upper limit to Newton’s Law is where the droplet size is so large that it requires a terminal velocity of such magnitude that excessive turbulence is created. For the Newton’s Law region, the upper limit to the Reynolds number is 200,000 and KCR = 18.13.

Separator Design & Construction

- Separators are usually characterized as vertical, horizontal, or spherical.



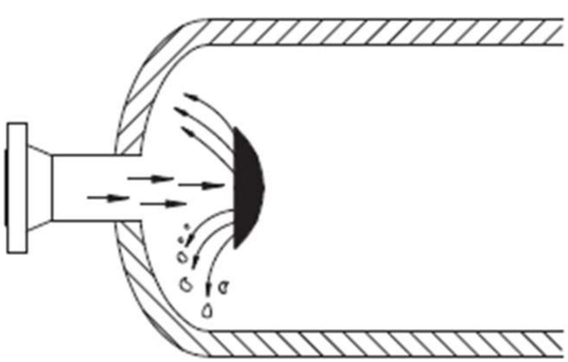


Separator Design & Construction

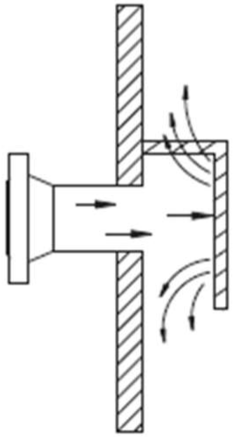
- Inlet Diverter: This abruptly changes the direction of flow by absorbing the momentum of the liquid and gas to separate. This results in the initial “gross” separation of liquid and gas.
    - no inlet device
    - diverter plate
    - half-pipe
    - vane-type
    - cyclonic
- Gravity Settling Section: This section is sized so that liquid droplets greater than 100–140 mm fall to the gas–liquid interface, while smaller liquid droplets remain with the gas. Liquid droplets, greater than 100 mm, are undesirable as they can overload the mist extractor at the separator outlet.
- Mist Extractor Section: Before the gas leaves the vessel, it passes through a coalescing section or mist extractor. This section uses coalescing elements that provide a large amount of surface area used to coalesce and remove the small droplets of liquid.

Separator Design & Construction

- Inlet Diverter:



Diverter Baffle



Tangential Baffle

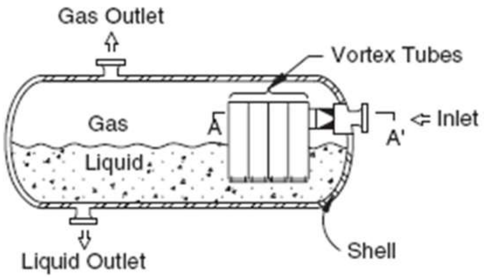


Fig.1

Elements of a Foamfree System

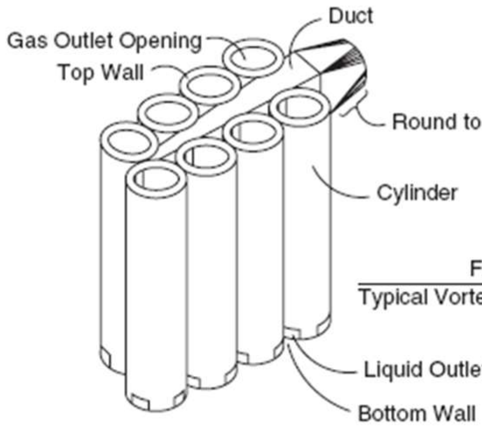


Fig.3

Typical Vortex Tube Cluster

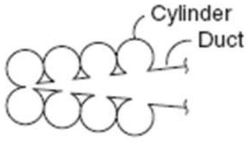


Fig.2

Section A-A'

Separator Design & Construction

Vortex Breakers:

- Liquid leaving a separator may form vortices or whirlpools, which can pull gas down into the liquid outlet.
- Therefore, separators are often equipped with vortex breakers, which prevent a vortex from developing when the liquid control valve is open. A vortex could suck some gas out of the vapor space and re-entrain it in the liquid outlet.

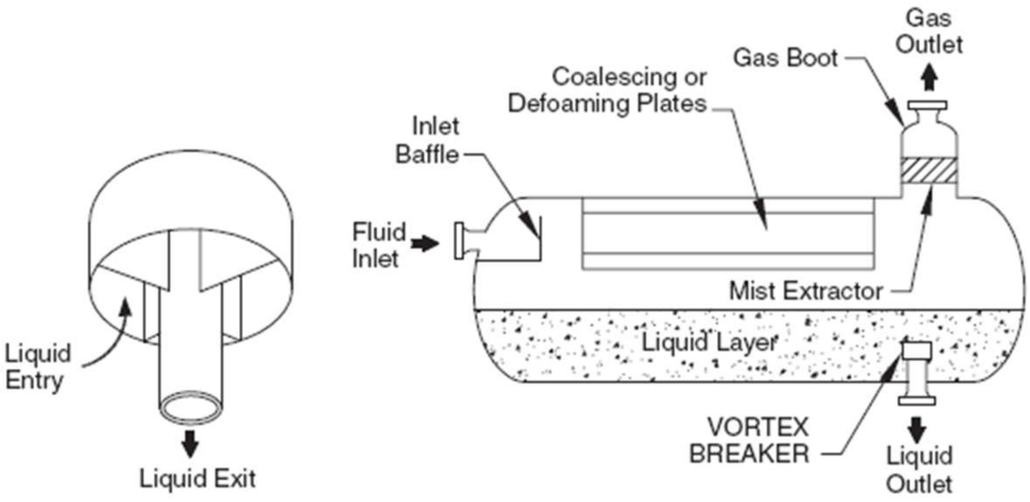


FIGURE 3.23. Vortex breaker.

Separator Design & Construction

Mist Extractors:

- Before a selection can be made, one must evaluate the following factors:
  - Size of droplets the separator must remove.
  - Pressure drop that can be tolerated in achieving the required level of removal.
  - Susceptibility of the separator to plugging by solids, if solids are present.
  - Liquid handling capability of the separator.
  - Whether the mist extractor/eliminator can be installed inside existing equipment, or if it requires a standalone vessel instead.
  - Availability of the materials of construction that are comparable with the process.
  - Cost of the mist extractor/eliminator itself and required vessels, piping, instrumentation, and utilities.

Separator Design & Construction

Mist Extractors:

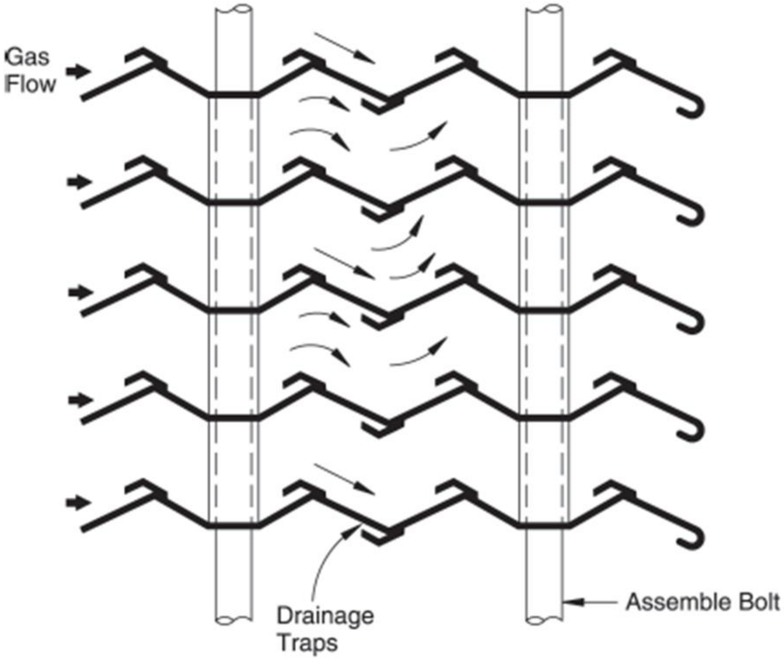


FIGURE 3.28. Vane-type element with corrugated plates and liquid drainage trays.

FIGURE 3.33. Example wire-mesh mist extractor (photo courtesy of ACS Industries, LP, Houston, TX).

Separator Design & Construction

- Separator Configurations :

  Factors to be considered for separator configuration selection include:

  - · How well will extraneous material (e.g. sand, mud, corrosion products) be handled?
  - · How much plot space will be required?
  - · Will the separator be too tall for transport if skidded?
  - · Is there enough interface surface for three-phase separation (e.g. gas/hydrocarbon/glycol liquid)?
  - · Can heating coils or sand jets be incorporated if required?
  - · How much surface area is available for degassing of separated liquid?
  - · Must surges in liquid flow be handled without large changes in level?
  - ·Is large liquid retention volume necessary?

Separator Design & Construction

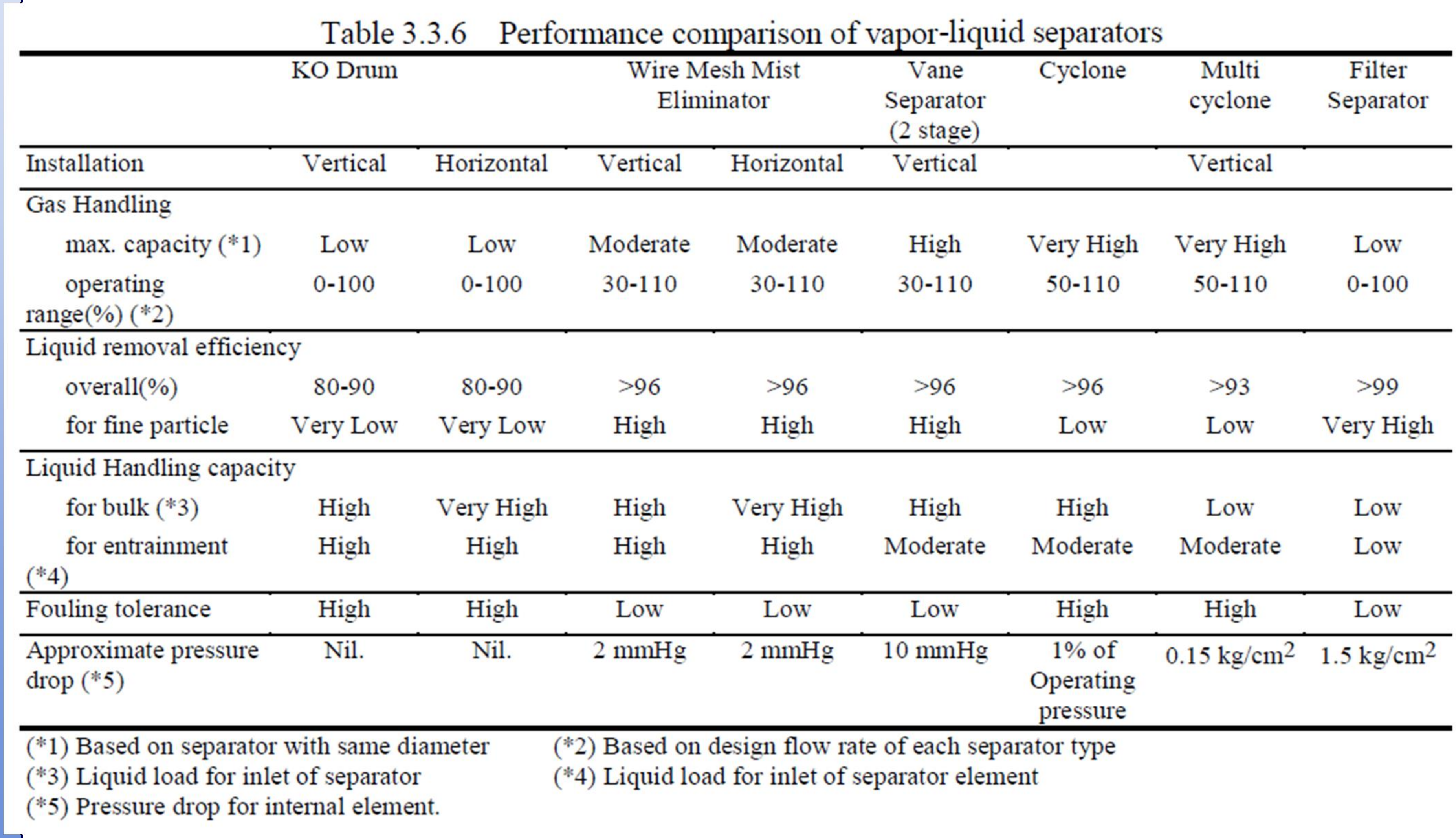


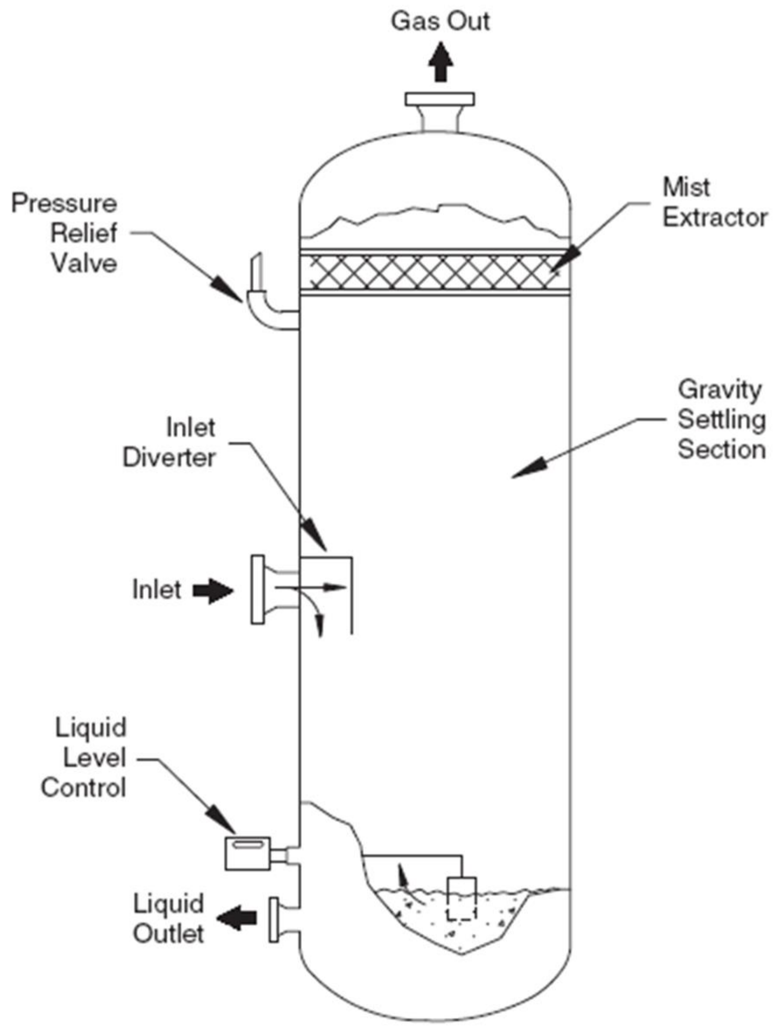
Table 3.3.6 Performance comparison of vapor-liquid separators

	KO Drum		Wire Mesh Mist Eliminator		Vane Separator (2 stage)	Cyclone	Multi cyclone	Filter Separator
Installation	Vertical	Horizontal	Vertical	Horizontal	Vertical		Vertical	
Gas Handling								
max. capacity (*1)	Low	Low	Moderate	Moderate	High	Very High	Very High	Low
operating range(%) (*2)	0-100	0-100	30-110	30-110	30-110	50-110	50-110	0-100
Liquid removal efficiency								
overall(%)	80-90	80-90	>96	>96	>96	>96	>93	>99
for fine particle	Very Low	Very Low	High	High	High	Low	Low	Very High
Liquid Handling capacity								
for bulk (*3)	High	Very High	High	Very High	High	High	Low	Low
for entrainment (*4)	High	High	High	High	Moderate	Moderate	Moderate	Low
Fouling tolerance	High	High	Low	Low	Low	High	High	Low
Approximate pressure drop (*5)	Nil.	Nil.	2 mmHg	2 mmHg	10 mmHg	1% of Operating pressure	0.15 kg/cm^2	1.5 kg/cm^2

(*1) Based on separator with same diameter
(*2) Based on design flow rate of each separator type
(*3) Liquid load for inlet of separator
(*4) Liquid load for inlet of separator element
(*5) Pressure drop for internal element.

Separator Design & Construction

- Vertical Separators:



•usually selected when the gas-liquid ratio is high or total gas volumes are low.

•Typical vertical separator L/D ratios are normally in the 2–4 range.

•Level control is not critical and liquid level can fluctuate several inches without affecting operating Efficiency

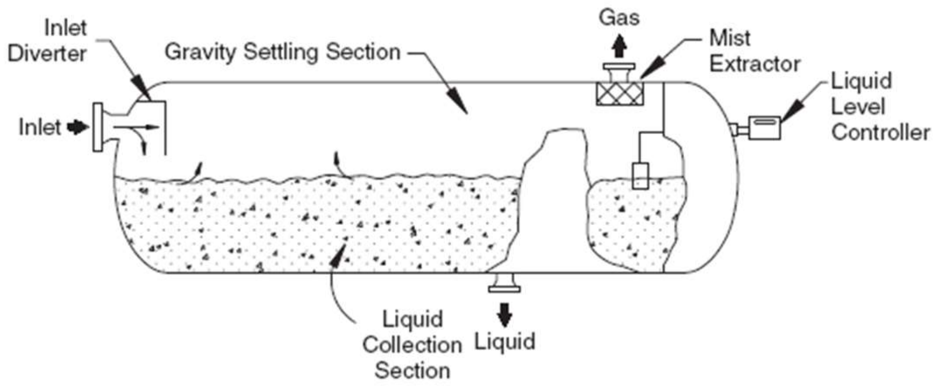
•Mist extractors can significantly reduce the required diameter of vertical separators.

•The separator occupies a small amount of plot space.

•The liquid level responds quickly to any liquid that enters thus tripping an alarm or shutdown.

Separator Design & Construction

- Horizontal Separators :



- most efficient where large volumes of total fluids and large amounts of dissolved gas are present with the liquid.
- Typical L/D ratios for horizontal separators normally fall in the range of 2.5–5.
- The greater liquid surface area in this configuration provides optimum conditions for releasing entrapped gas.
- The horizontal configuration would handle a foaming liquid better than a vertical.
- Increased slug capacity is obtained through shortened retention time and increased liquid level.

Gas-Liquid Separator Design

Slenderness Ratio (Length/Diameter):

- For each vessel design, a combination of L and D exists that will minimize the cost of the vessel.
- It can be shown that the smaller the diameter, the less the vessel will weigh and thus the lower its cost.
- The L/D ratio for all process vessels should be within the range:

  $1.5 \le L/D \le 6$, except in the case of surge vessels operating at atmospheric conditions; in such cases, it is cheaper to use smaller L/D ratios.
- If $L/D > 4$ or 5 → re-entrainment could become a problem. This should be checked for $L/D > 4$.

$2 \le L/D \le 3$	for	$P \le 4$ bara
$3 < L/D \le 5$	for	$P > 4$ bara

Gas-Liquid Separator Design

Selecting proper Diameter and Length :

- When making a final selection, it is always more economical to select a standard vessel size. (Refer to API-12J)
- Vessels with outside diameters up through 24 in. (600 mm) have nominal pipe dimensions.
- Vessels with outside diameters larger than 24 in. (600 mm) are typically rolled from plate with diameter increments of 6 in. (150 mm).
- The shell seam-to-seam length is expanded in 2.5-ft (750-mm) segments and is usually from 5 ft to 10 ft (1500–3000 mm).

Gas-Liquid Separator Design

Separators Without Mist Eliminator :

- To design a separator without a mist extractor, the minimum size diameter droplet to be removed must be set. Typically this diameter is in the range of 150 to 2,000 microns.
- Separators without mist extractors are designed for gravity settling using basic gravity settling equations.

Horizontal Vessels Length (without liquid retention):

$$L = \frac{4\,Q_A}{\pi\,V_t\,D_v}$$

Gas-Liquid Separator Design

Liquid Handling:

- The design criterion for separator liquid handling capacity is typically based on the following two main considerations:
  - Liquid degassing requirements.
  - Process control/stability requirements.
- Liquid capacity is typically specified in terms of residence time, which must be translated into vessel layout requirements for

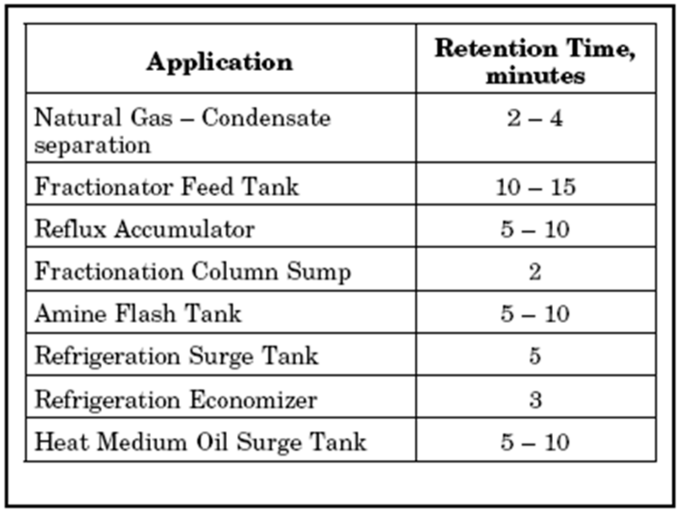
$$U = \frac{W\,(t)}{1440}$$

U = volume of settling section, bbl

W = total liquid flow rate, bbl/day

FIG. 7-20

Typical Retention Times for Gas/Liquid Separator



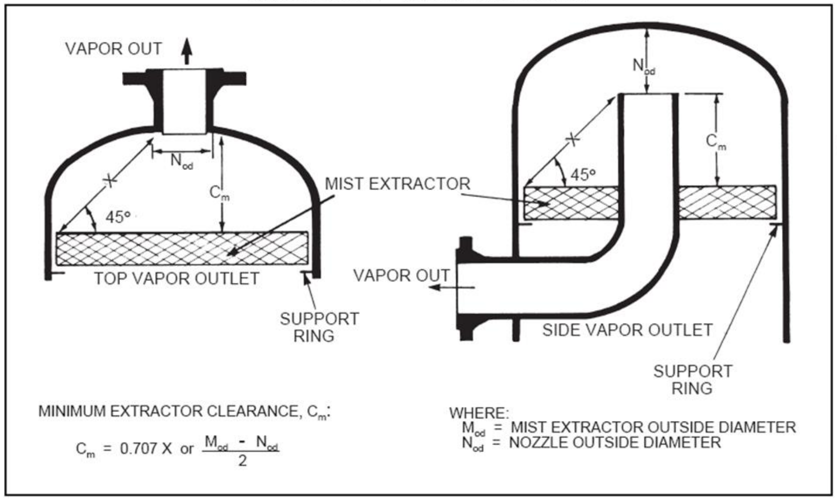
Application	**Retention Time, minutes**
Natural Gas – Condensate separation	2 – 4
Fractionator Feed Tank	10 – 15
Reflux Accumulator	5 – 10
Fractionation Column Sump	2
Amine Flash Tank	5 – 10
Refrigeration Surge Tank	5
Refrigeration Economizer	3
Heat Medium Oil Surge Tank	5 – 10

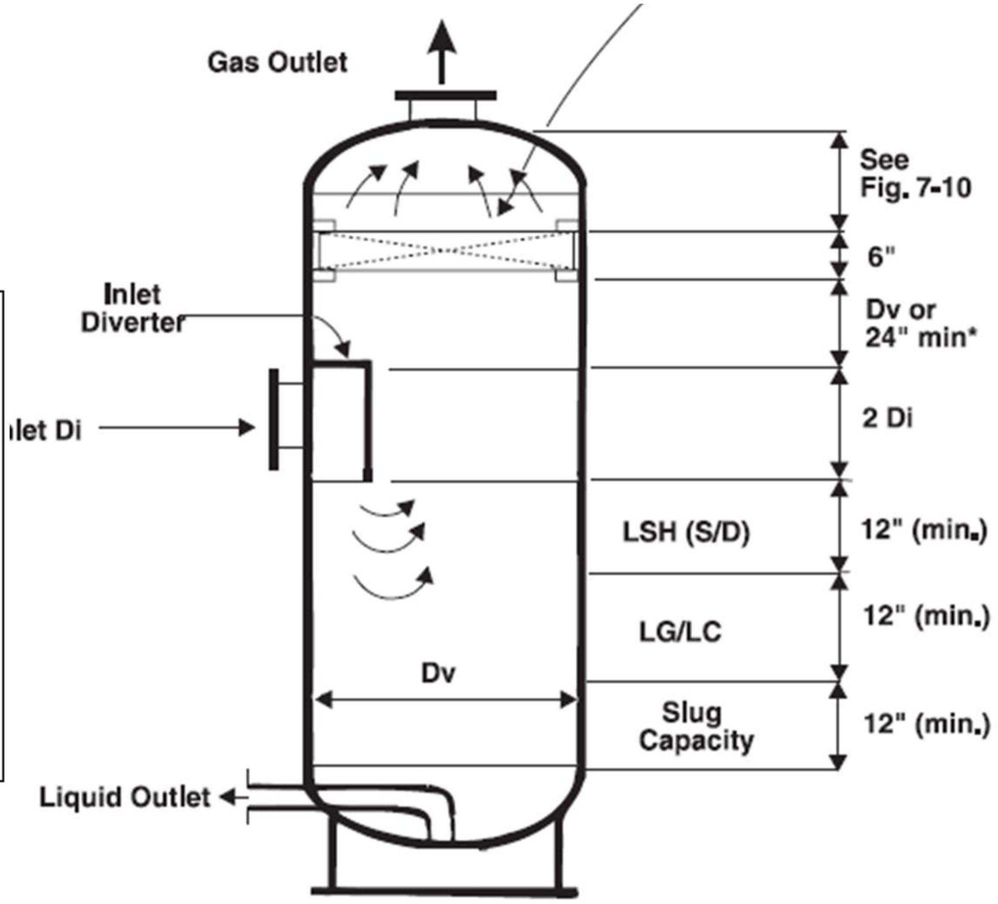
Gas-Liquid Separator Design

Liquid Handling:

FIG. 7-10

Minimum Clearance — Mesh Type Mist Eliminators





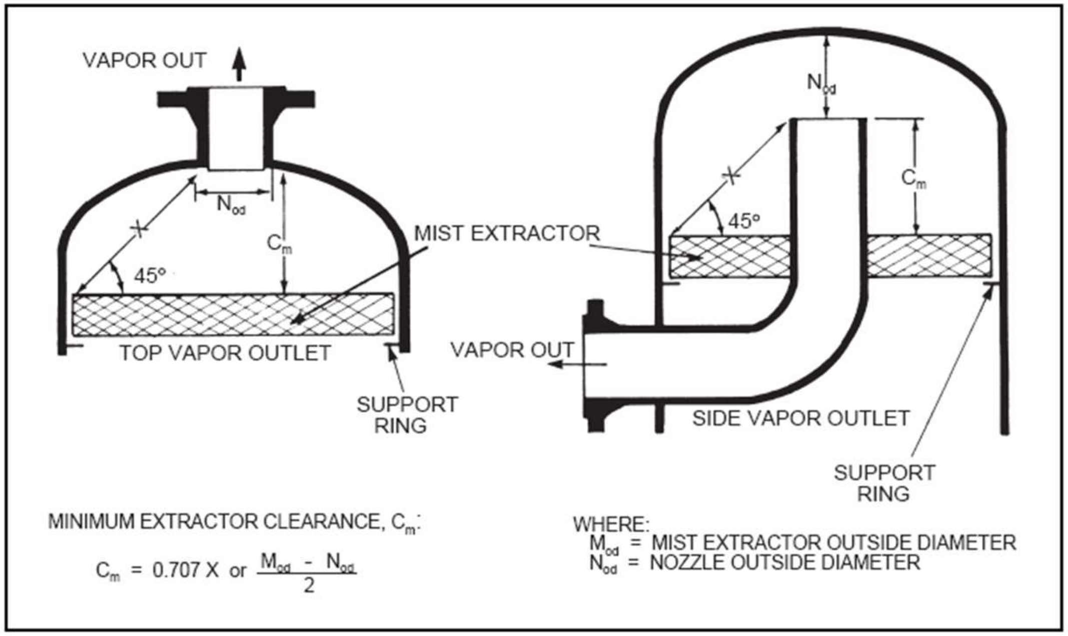
LSH (S/D) Level Switch High (Shutdown)
LG/LC Level Gauge/Level Controller

Gas-Liquid Separator Design

Separators With Mist Eliminator :

- Removal of droplets down to 10 microns or smaller may be possible with these pads.
- In plants where fouling or hydrate formation is possible or expected, mesh pads are typically not used. In these services vane or centrifugal type separators are generally more appropriate.
- Most installations will use a 150 mm thick pad with 144-192 kg/m3 bulk density. Minimum recommended pad thickness is 100 mm.
- Quoted liquid carryover from the various types of mist extraction devices are usually in the range of 0.1 - 1 gal/MMscf.

Example Minimum Clearance — Mesh Type Mist Eliminators



MINIMUM EXTRACTOR CLEARANCE, C_m:

$$C_m = 0.707 \text{ X or } \frac{M_{od} - N_{od}}{2}$$

WHERE:
M_{od} = MIST EXTRACTOR OUTSIDE DIAMETER
N_{od} = NOZZLE OUTSIDE DIAMETER

Gas-Liquid Separator Design

Separators With Mist Eliminator (GPSA) :

$$V_t = K\sqrt{\frac{\rho_l - \rho_g}{\rho_g}}$$

Mesh Pad Separation Performance

Droplet removal efficiency:	99–99.5% removal of 3–10 micron droplets. Higher removal efficiency is for denser, thicker pads and/or smaller wire/co-knit fiber diameter.
Gas capacity, K, ft/sec	0.22–0.39. Generally, the lower capacities correspond to the mesh pad designs with the highest droplet removal efficiencies.

Typical Vane Pack Separation Performance

Droplet removal efficiency:	99% removal of droplets greater than 10–40 microns. Higher removal efficiency is for thicker packs, with closer vane spacings and more passes (bends).
Gas capacity, K, ft/sec	Horizontal flow: 0.9–1.0 Vertical up-flow: 0.4–0.5 The higher capacities are generally associated with pocketed vane designs.

Typical K & C Factors for Sizing Woven Wire Demisters

Separator Type	K Factor (m/s)	C Factor (m/h)
Horizontal	0.12 to 0.15	430 to 540
Vertical	0.05 to 0.11	200 to 400
Spherical	0.05 to 0.11	220 to 400
Wet Steam	0.076	270
Most vapors under vacuum	0.061	220
Salt & Caustic Evaporators	0.046	160
Adjustment of K & C Factor for Pressure - % of design value[15]		
Atmospheric	100	
1000 kPa	90	
2000 kPa	85	
4000 kPa	80	
8000 kPa	75	

- For glycol and amine solutions, multiply K by 0.6 - 0.8.
- Typically use one-half of the above K or C values for approximate sizing of vertical separators without wire demisters.
- For compressor suction scrubbers and expander inlet separators multiply K by 0.7 - 0.8.

Typical Values of K for Vertical Separators

Height, feet	K, ft/sec
5	0.12 – 0.24
10 or taller	0.18 – 0.35

* assumes vessel is equipped with a wire-mesh mist extractor

Values of K for Horizontal Separators

Length, ft	K, ft/sec
10	0.40 – 0.50
Other	$K_{10}\left(\frac{L}{10}\right)^{0.56}$

* assumes vessel is equipped with a wire-mesh mist extractor

Gas-Liquid Separator Design

Separators With Mist Eliminator :

Technip :

Critical velocity:

$$U_G^* = 0.381 \times K_V \sqrt{\frac{(\rho_L - \rho_G)}{\rho_G}} \quad \text{(m/s)}$$

$$\log(K_V) = -0.876 - 0.837 \times \log(B) - 0.324 \times [\log(B)]^2 \quad (0.006 \leqslant B \leqslant 6)$$

with: $$B = \frac{W_L}{W_G}\sqrt{\frac{\rho_G}{\rho_L}} \quad \text{(dimensionless)}$$

if $B < 0.006$ use $K_V = 0.2$

if $B > 6$ use $K_V = 0.02$

W_L and W_G are the liquid and gas mass flow rates.

Foster-Wheeler :

$$V_c = 4.57\sqrt{\frac{\rho_l}{\rho_g} - 1}$$

where V_c = critical entrainment velocity, cm/sec

Shell :

The vessel diameter shall satisfy

1. **the primary separation criterion** (i.e. separation by Schoepentoeter):

$$\lambda_{max} = Q^*_{max} / (\pi D^2_{min} / 4) = 0.1 + 0.008\,\rho_G^{-0.14}\,\phi_{feed}^{-0.76}$$

giving $D \geq 1.13\sqrt{Q^*_{max} / \lambda_{max}}$

If **no slugs** are expected, the above criterion shall **not exceed**

$\lambda_{max} = 0.20$ m/s

If **slugs** are expected:

$\lambda_{max} = 0.10$ m/s (to prevent overloading of the vane pack)

Gas-Liquid Separator Design

Separators With or Without Mist Eliminator :

Total :

$$V_s = K\left[\frac{\rho_L - \rho_V}{\rho_V}\right]^{1/2}$$

$\rho_{L,V}$ - liquid or vapour density kg/m^3

V_s - settling velocity m/s

K = correlating parameter m/s

D - particle diameter -microns

C - drag coefficient

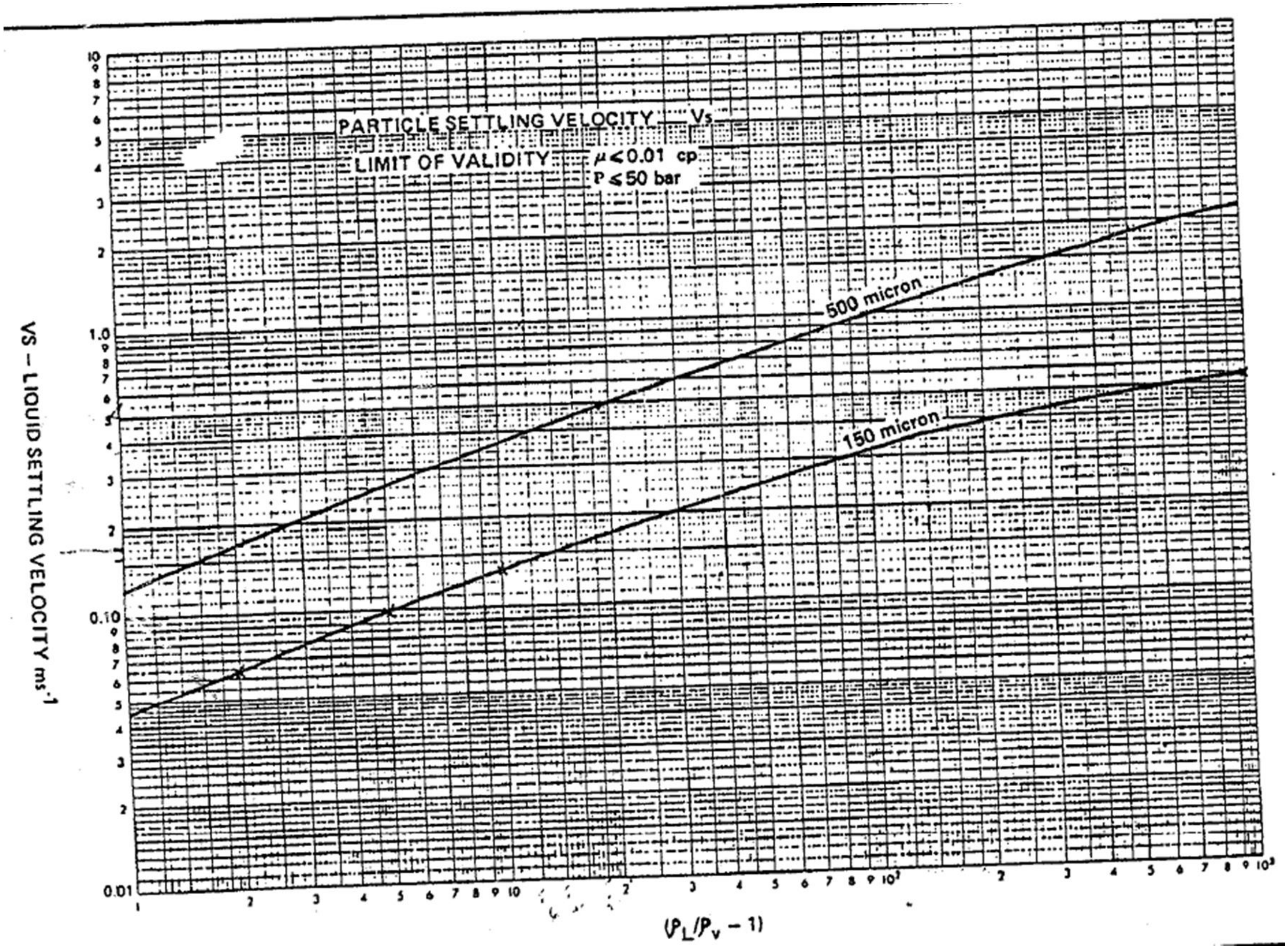
μ - vapour viscosity - centipoise

$$K = 0.003616\left(\frac{D}{C}\right)^{1/2}$$

- For medium and low pressure with gases of viscosity less than 0.01 cp Figure 1 can be used to estimate Vs.
- For higher pressures (> 50 bar) or viscosities in excess of 0.01 cp it is necessary to calculate Vs. The drag coefficient C is calculated using Figure in slide 9.

Gas-Liquid Separator Design

Figure 1



Gas-Liquid Separator Design

Vessel Volumes:

Horizontal Cylinder:

$$V_c = A1 \times L$$

- Partial volumes and areas of a horizontal vessel can be calculated using the estimated using the following equations:

$$A1 = \left[\frac{D^2}{4}\,\mathrm{Arccos}\left(\frac{D-2h}{D}\right)\right] - \left[\left(\frac{D}{2}-h\right)\left(Dh-h^2\right)^{1/2}\right] \text{ in } m^2$$

D = inside diameter of the vessel, (m),

h = distance between the cylinder bottom and the liquid level, (m),

Arccos in radians

2 Dished Heads

$$V_{dh} = 0.21543 \times h^2 \times (1.5 \times D - h) \quad \text{in } m^3$$

2 Elliptical Heads

$$V_{eh} = 0.52194 \times h^2 \times (1.5 \times D - h) \quad \text{in } m^3$$

2 Hemispherical Heads

$$V_{hh} = 1.047 \times h^2 \times (1.5 \times D - h) \quad \text{in } m^3$$

Gas-Liquid Separator Design

Vessel Volumes:

Horizontal Cylinder: $V_c = A1 \times L$

- Partial volumes and areas of a horizontal vessel can be calculated using the following equations:

$A1/A_T=(\theta - \sin\theta)/(2\pi)$

$\theta = 2 \arccos(1-2\,h/D)$, θ in radians

D = inside diameter of the vessel, (m),

h = distance between the cylinder bottom and the liquid level, (m),

2 Dished Heads $V_{dh} = 0.21543 \times h^2 \times (1.5 \times D - h)$ in m^3

2 Elliptical Heads $V_{eh} = 0.52194 \times h^2 \times (1.5 \times D - h)$ in m^3

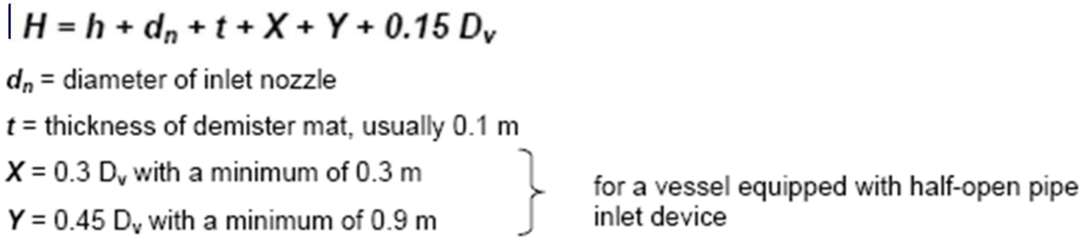
2 Hemispherical Heads $V_{hh} = 1.047 \times h^2 \times (1.5 \times D - h)$ in m^3

Volume up to Baffle for depth (elliptical heads) $= \frac{0.52194h^2(1.5D - h))}{2} + (A1 \times B)$

Gas-Liquid Separator Design

Vertical Separators with mist extractor sizing procedure:

1. Select a proper K factor and de-rate it, calculate settling velocity
2. Calculate allowable gas velocity based on 85% of settling velocity (TOTAL procedure) to allow sufficient margin (conservative) or take 100% of settling velocity based on proper inlet devices (GPSA).
3. Calculate drum diameter and select a diameter according to API12J recommendations (slide 23) (Add 3 to 6 in. to drum diameter to accommodate a support ring and round up to the next 6 in).
4. Calculate height as follows : (Let h be the height of vessel required for liquid



$$H = h + d_n + t + X + Y + 0.15\, D_v$$

d_n = diameter of inlet nozzle

t = thickness of demister mat, usually 0.1 m

X = 0.3 D_v with a minimum of 0.3 m

Y = 0.45 D_v with a minimum of 0.9 m

$\Big\}$ for a vessel equipped with half-open pipe inlet device

X : distance between HHLL to bottom inlet nozzle

Y : distance between top inlet nozzle to demister bottom

Gas-Liquid Separator Design

Vertical Separators with mist extractor sizing procedure (cont.):

- Calculate h (hold-up length) based on design criteria in slide 24 or use the following minimum requirement between LA(L) and LA(H) which shall be applied in the absence of other overriding process considerations :

  Automatic control

  4 minutes for product to storage

  5 minutes for feed to a furnace

  4 minutes for other applications

  Manual control

  20 minutes.

5. For vessel diameters of 0.8 m and greater, a vane-type inlet device is recommended. The diameter of the nozzle, may be taken equal to that of the feed pipe, but the following two criteria shall also be satisfied:

$$\rho_{m}.V^{2} \leq 6000\ kg/m.s^{2}$$

$$\rho_{g}.V^{2}_{g.in} \leq 3750\ kg/m.s^{2}$$

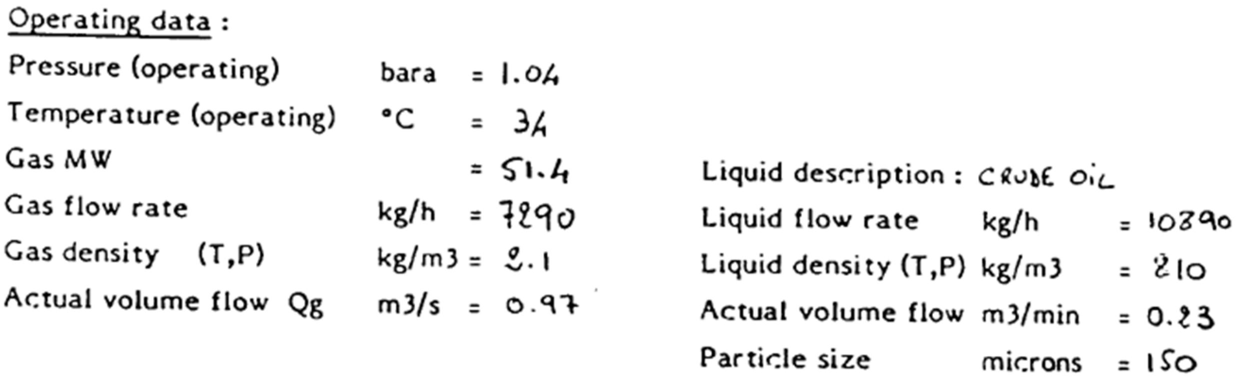
Gas-Liquid Separator Design

Vertical Separators with mist extractor sizing procedure (cont.):

6. When the vessel diameter is less than 0.8 m the feed nozzle should be fitted with a half-open pipe inlet device. The nozzle diameter may be taken equal to that of the feed pipe but the product $\rho_g \times V_g^2$ shall not exceed 1500 kg/m.s² .
7. The diameter of the gas outlet nozzle should normally be taken equal to that of the outlet pipe, but the product $\rho_g \times V_g^2$,out shall not exceed 3750 kg/m.s².

   The diameter of the liquid outlet nozzle shall be choosen such that the velocity in it does not exceed 1 m/s, but should preferably be lower. The nozzle shall be equipped with a vortex breaker.
8. Check the slenderness ratio to be between 2 and 4 , if not change diameter and redo calculations.

Example



Operating data :

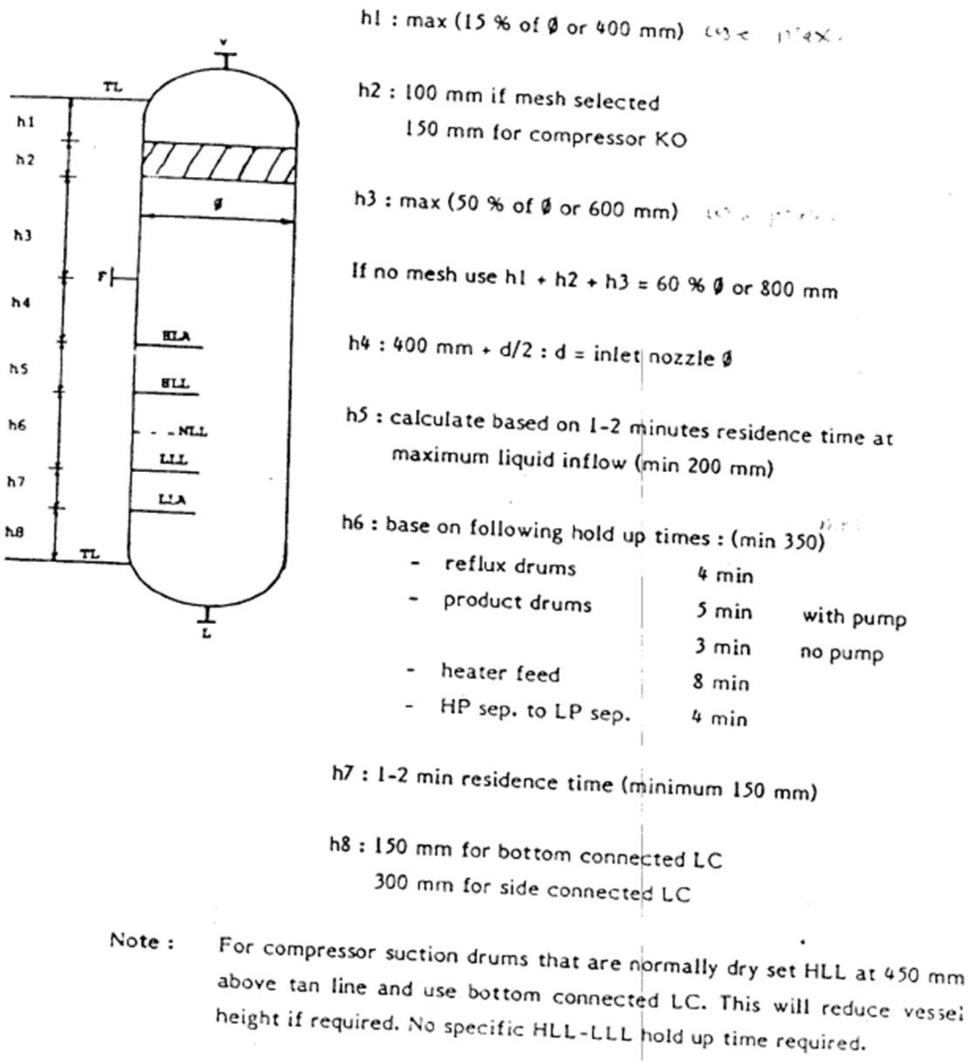
Pressure (operating) bara = 1.04
Temperature (operating) °C = 34
Gas MW = 51.4
Gas flow rate kg/h = 7290
Gas density (T,P) kg/m3 = 2.1
Actual volume flow Qg m3/s = 0.97

Liquid description : CRUDE OIL
Liquid flow rate kg/h = 10890
Liquid density (T,P) kg/m3 = 810
Actual volume flow m3/min = 0.23
Particle size microns = 150

Gas-Liquid Separator Design

Vertical Separators with mist extractor sizing procedure (cont.):

- TOTAL procedure for height calculation :



h1 : max (15 % of ø or 400 mm)

h2 : 100 mm if mesh selected
150 mm for compressor KO

h3 : max (50 % of ø or 600 mm)

If no mesh use h1 + h2 + h3 = 60 % ø or 800 mm

h4 : 400 mm + d/2 : d = inlet nozzle ø

h5 : calculate based on 1-2 minutes residence time at maximum liquid inflow (min 200 mm)

h6 : base on following hold up times : (min 350)

- reflux drums	4 min	
- product drums	5 min	with pump
	3 min	no pump
- heater feed	8 min	
- HP sep. to LP sep.	4 min	

h7 : 1-2 min residence time (minimum 150 mm)

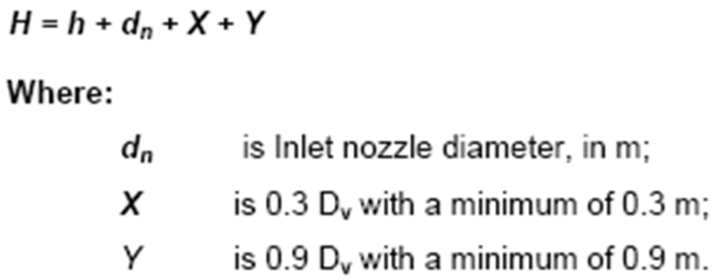
h8 : 150 mm for bottom connected LC
300 mm for side connected LC

Note : For compressor suction drums that are normally dry set HLL at 450 mm above tan line and use bottom connected LC. This will reduce vessel height if required. No specific HLL-LLL hold up time required.

Gas-Liquid Separator Design

Vertical Separators without mist extractor sizing procedure:

1. Calculate settling velocity based on settling equations in slide 8,9 (use 150micron particles typically).
2. Calculate allowable gas velocity based on 85% of settling velocity (TOTAL procedure) to allow sufficient margin (conservative) or take 100% of settling velocity based on proper inlet devices (GPSA).
3. Calculate drum diameter and select a diameter according to API12J recommendations (slide 23).
4. Calculate height as follows : (Let h be the height of vessel required for liquid hold-up)



$$H = h + d_n + X + Y$$

Where:

d_n is Inlet nozzle diameter, in m;

X is 0.3 D_v with a minimum of 0.3 m;

Y is 0.9 D_v with a minimum of 0.9 m.

Gas-Liquid Separator Design

Vertical Separators without mist extractor sizing procedure (cont.):

5. The feed nozzle shall be fitted with a half open pipe or a flow diverting box inlet device. The nozzle diameter, d_n, may be taken equal to that of the feed pipe but the product $\rho_g \times V_g^2$ shall not exceed 1500 kg/m.s².

   The diameter of the gas outlet nozzle should normally be taken equal to that of the outlet pipe, but the product $\rho_g \times V_g^2$,out shall not exceed 3750 kg/m.s².

   The diameter of the liquid outlet nozzle shall be choosen such that the velocity in it does not exceed 1 m/s, but should preferably be lower. The nozzle shall be equipped with a vortex breaker.

6. Check the slenderness ratio to be between 2 and 4 , if not change diameter and redo calculations.

Gas-Liquid Separator Design

Horizontal Separators with mist extractor sizing procedure:

1. Calculate settling velocity based on settling equations in slide 8,9 (use 500micron particles if vane type mist extractor and 150micron for wire mesh).
2. Calculate allowable gas velocity based on 85% of settling velocity (TOTAL procedure) to allow sufficient margin (conservative) or take 100% of settling velocity based on proper inlet devices (GPSA).
3. Select a diameter according to API12J recommendations (slide 23).
4. Select a slenderness ratio based on recommendations in slide 22 and calculate preliminary L. ($At = \pi * D^2/4$)
5. Calculate liquid area (Al) based on hold-up requirements :

   Al = (Total liquid vol. flowrate) / hold-up Time / L
6. Calculate hl (liquid height) from this figure.

Gas-Liquid Separator Design

Horizontal Separators with mist extractor sizing procedure (cont.):

7. Calculate vapor height : $hv = D - hl$
8. Calculate liquid drop-out time : $\theta = hv$ / settling velocity
9. Calculate vapor velocity : $Uv = Qv / Av$, $Av = At - Al$
10. Calculate minimum length : $L_{min} = Uv * \theta$
11. If $L_{min} \le L$, the selected L is ok , if not change diameter and return to step 5.

Gas-Liquid Separator Design

Horizontal Separators without mist extractor sizing procedure:

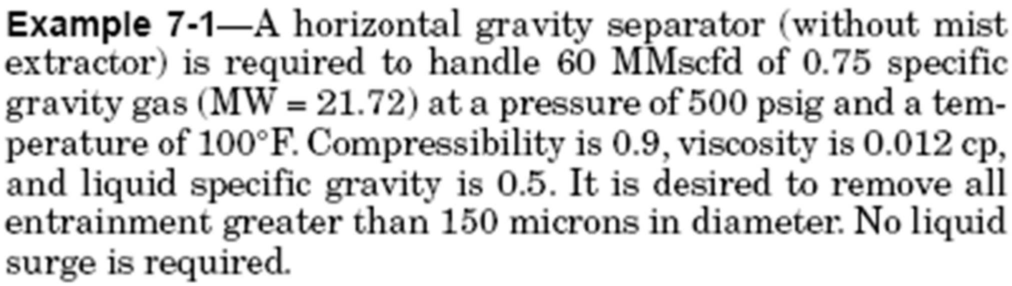
1. Calculate settling velocity based on settling equations in slide 8,9 (use 150micron particle diameter, if it is a flare KO drum use 300-600microns).
2. Calculate allowable gas velocity based on 85% of settling velocity (TOTAL procedure) to allow sufficient margin (conservative) or take 100% of settling velocity based on proper inlet devices (GPSA).
3. Select a diameter according to API12J recommendations (slide 23).
4. Select a slenderness ratio based on recommendations in slide 22 and calculate preliminary L then calculate total area. ($At = \pi*D^2/4$)
5. Calculate liquid area (Al) based on hold-up requirements :

   Al = (Total liquid vol. flowrate) / hold-up Time / L
6. Calculate hl (liquid height) from this figure.

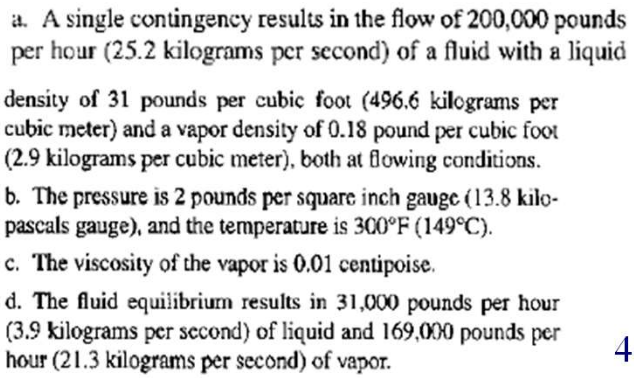
Gas-Liquid Separator Design

Horizontal Separators without mist extractor sizing procedure (cont.):

7. Calculate vapor height : hv = D - hl
8. Calculate liquid drop-out time : θ = hv / settling velocity
9. Calculate vapor velocity : Uv = Qv / Av , Av = At - Al
10. Calculate minimum length : L_{min} = Uv * θ
11. If L_{min}<= L , the selected L is ok , if not change diameter and return to step 5.



Example 7-1—A horizontal gravity separator (without mist extractor) is required to handle 60 MMscfd of 0.75 specific gravity gas (MW = 21.72) at a pressure of 500 psig and a temperature of 100°F. Compressibility is 0.9, viscosity is 0.012 cp, and liquid specific gravity is 0.5. It is desired to remove all entrainment greater than 150 microns in diameter. No liquid surge is required.



a. A single contingency results in the flow of 200,000 pounds per hour (25.2 kilograms per second) of a fluid with a liquid density of 31 pounds per cubic foot (496.6 kilograms per cubic meter) and a vapor density of 0.18 pound per cubic foot (2.9 kilograms per cubic meter), both at flowing conditions.

b. The pressure is 2 pounds per square inch gauge (13.8 kilopascals gauge), and the temperature is 300°F (149°C).

c. The viscosity of the vapor is 0.01 centipoise.

d. The fluid equilibrium results in 31,000 pounds per hour (3.9 kilograms per second) of liquid and 169,000 pounds per hour (21.3 kilograms per second) of vapor.

Gas-Liquid Separator Design

Horizontal Separators with or without mist extractor sizing procedure (Total):

1. Calculate settling velocity V_s.
2. Derate this by F =0.85 and calculate required vapour velocity *V_m m /s.*
3. Evaluate required vapour cross sectional area, A_v.
4. Assume drum is 70 % full i.e *h/D = 0.7 and evaluate drum diameter to give required A_v* ,(to nearest 50 mm). For "dry" vessels use *h/D = 0.35.*
5. For required (liquid surge volume) calculate volume at HLL, if insufficient adjust D or L (note if *L/D changes significantly recheck A_v using new V_m).*
6. Set position of LLL in drum and confirm required surge volume between HLL-LLL. If volume is insufficient increase D, L or h. Include volumes In heads.

Gas-Liquid Separator Design

Horizontal Separators with or without mist extractor sizing procedure (Total):

7. When setting LLL height take into account any LSLL, LSL alarms and vortex breakers which may set minimum value usable. Usually 300-350 mm..

Notes :

- L is designated as the flow path length i.e distance between inlet and outlet nozzle. L' is the tangent-tangent length. For 1st estimates

  $L' = L + 1.5\ d_1 + 1.5\ d_2$

  d_1 = inlet nozzle diameter

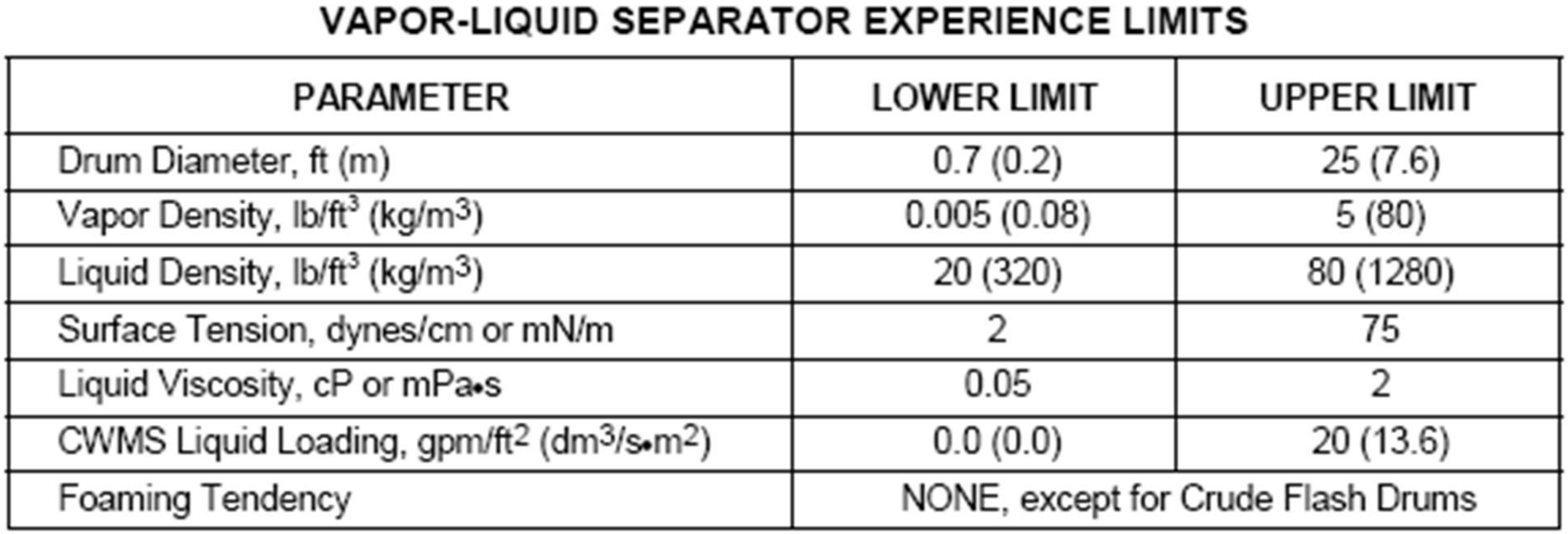
  d_2 = outlet nozzle diameter

- For high volumetric flows of gas with small liquid volumes consider using split flow arrangement. Design is as above but with half vapour volume *flow.*

- Normal design is with top entry, exit nozzles. However if space is limiting (primarily offshore) head mounted nozzles can be used to increase flowpath

Gas-Liquid Separator Design

Vapor-Liquid Experience Limits:



VAPOR-LIQUID SEPARATOR EXPERIENCE LIMITS

PARAMETER	LOWER LIMIT	UPPER LIMIT
Drum Diameter, ft (m)	0.7 (0.2)	25 (7.6)
Vapor Density, lb/ft^3 (kg/m^3)	0.005 (0.08)	5 (80)
Liquid Density, lb/ft^3 (kg/m^3)	20 (320)	80 (1280)
Surface Tension, dynes/cm or mN/m	2	75
Liquid Viscosity, cP or mPa•s	0.05	2
CWMS Liquid Loading, gpm/ft^2 (dm^3/s•m^2)	0.0 (0.0)	20 (13.6)
Foaming Tendency	NONE, except for Crude Flash Drums	

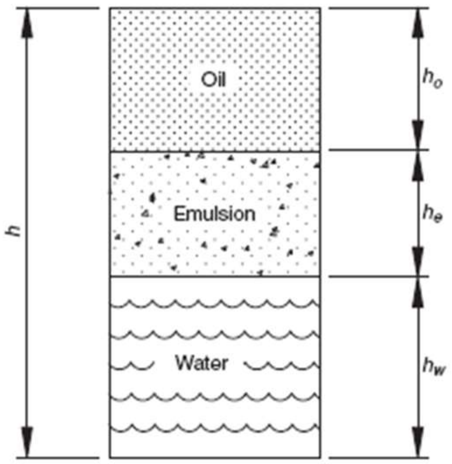
Gas-Liquid Separator Design

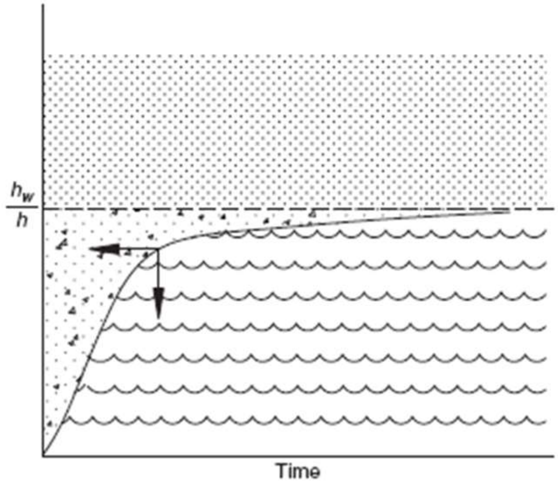
Selection between Horizontal and vertical separators:

- Gravity separation is more efficient in horizontal vessels than in vertical vessels.
- Horizontal separators have greater interface areas, which enhances phase equilibrium. This is especially true if foam or emulsion collect at the gas–oil interface. Thus, from a process perspective, horizontal vessels are preferred.
- Horizontals do have several drawbacks, which could lead to a preference for a vertical vessel in certain situations:
  - Horizontal separators are not as good as vertical separators in handling solids.
  - Horizontal vessels require more plan area to perform the same separation as vertical vessels.
  - Small-diameter horizontal vessels [3-ft (1.5-m) diameter and smaller] have less liquid surge capacity than vertical vessels sized for the same steady-state flow rate.
- In summary, horizontal vessels are most economical for normal oil–water separation, particularly where there may be problems with emulsions, foam, or high gas–liquid ratios.

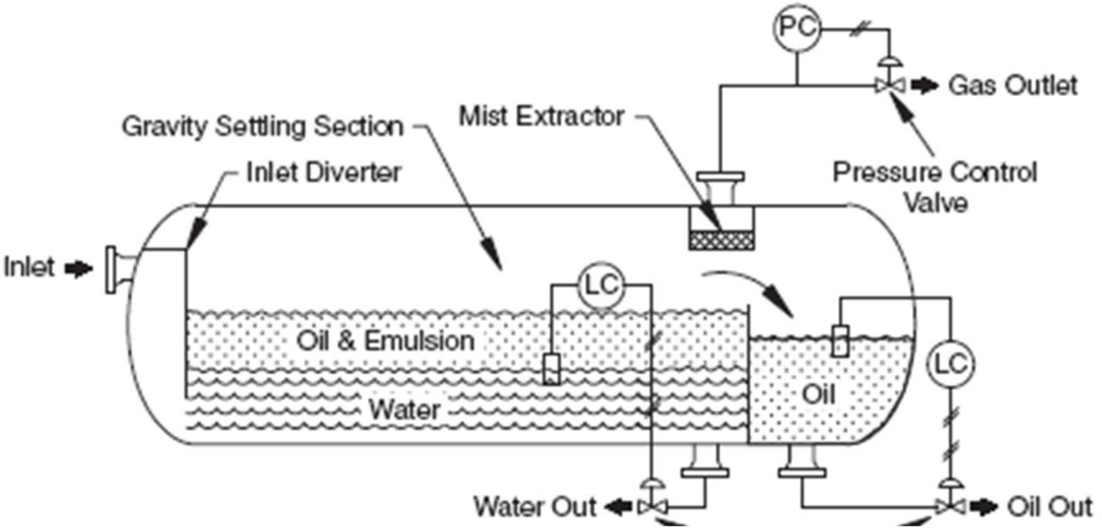
Gas-Liquid-Liquid Separator Design

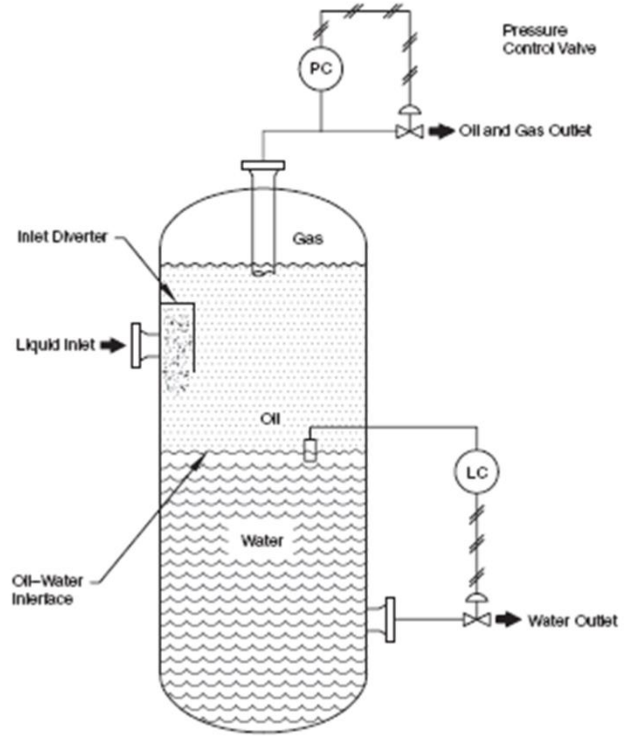
- When oil and water are mixed with some intensity and then allowed to settle, a layer of relatively clean free water will appear at the bottom.

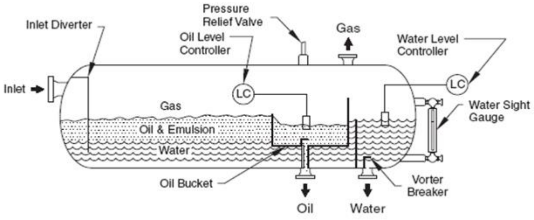


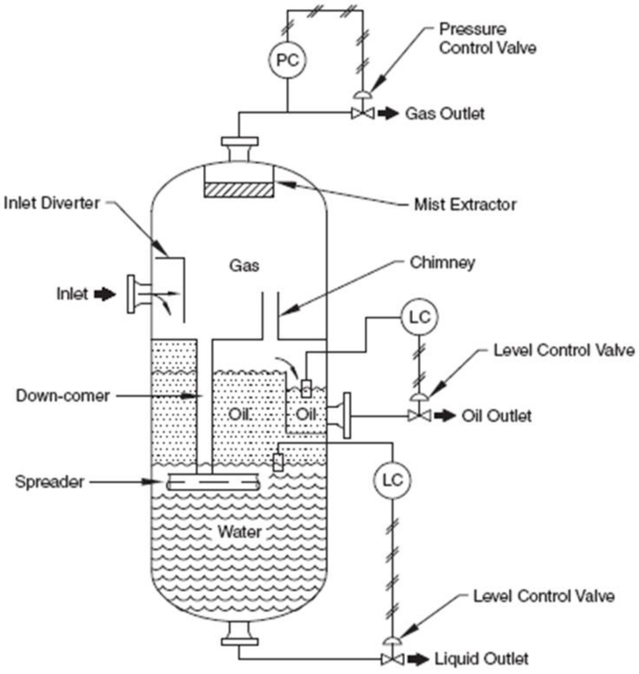


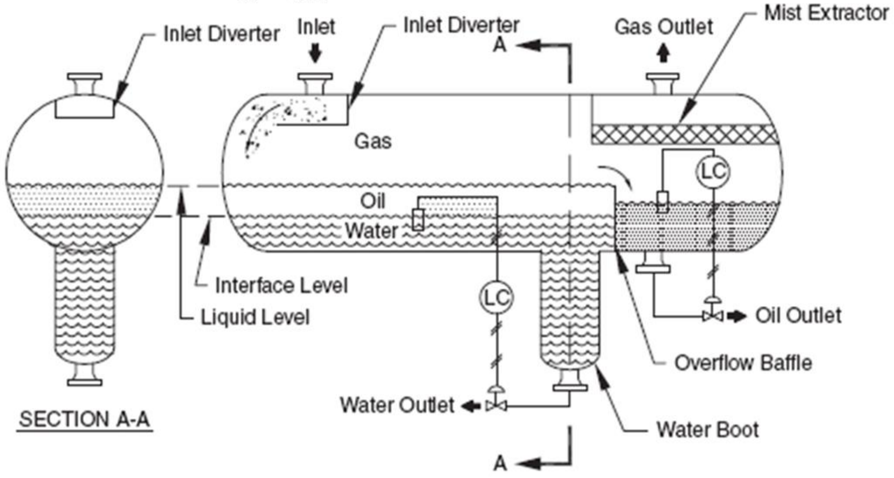
Gas-Liquid-Liquid Separator Design





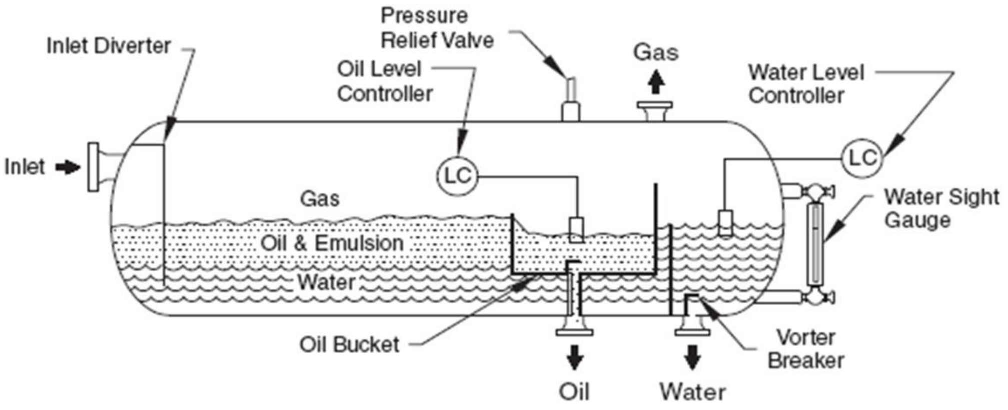




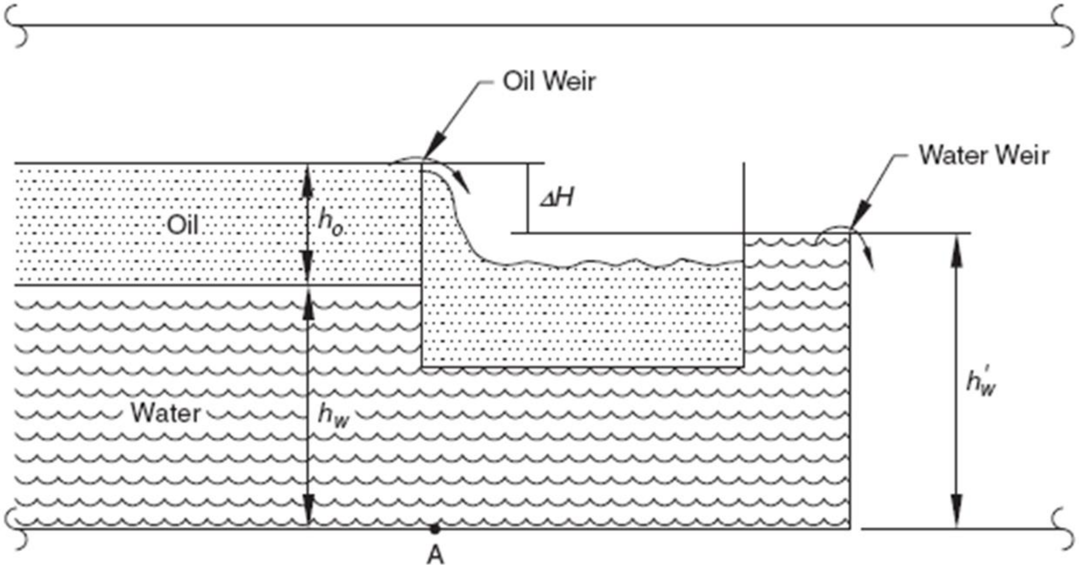


Gas-Liquid-Liquid Separator Design

- Three-phase separators with a bucket and weir design are most effective with high water-to-oil flow rates and/or small density differences.

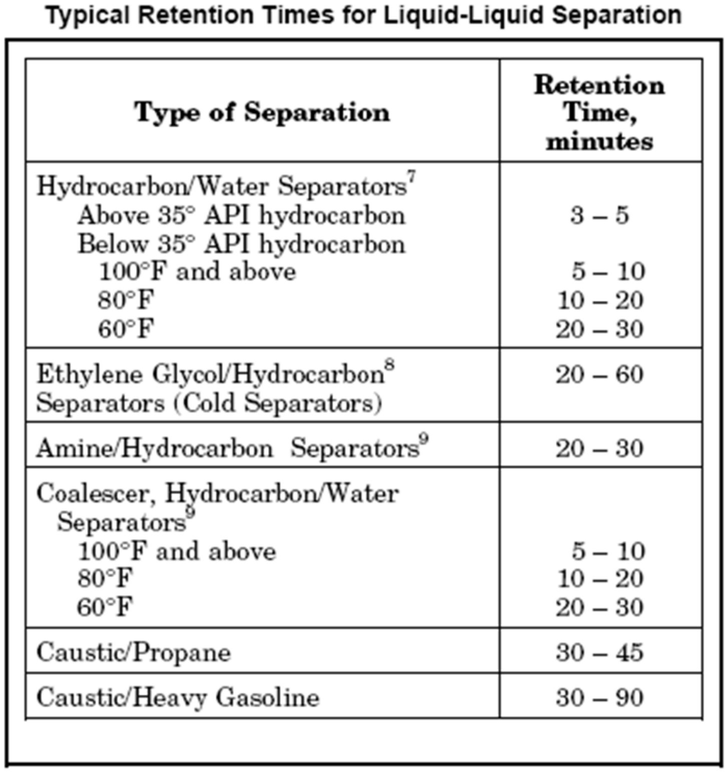


$$\Delta h = h_o\left[1 - \left(\frac{\rho_o}{\rho_w}\right)\right]$$



Gas-Liquid-Liquid Separator Design

- The gas handling requirements for three-phase separation are dealt with in a similar manner as discussed for two-phase separation.
- Traditionally, sizing for liquid-liquid separation has involved specification of liquid residence times.
- The gas capacity and retention time considerations establish certain acceptable combinations of diameter and length.



Typical Retention Times for Liquid-Liquid Separation

Type of Separation	**Retention Time, minutes**
Hydrocarbon/Water Separators[7]	
Above 35° API hydrocarbon	3 – 5
Below 35° API hydrocarbon	
100°F and above	5 – 10
80°F	10 – 20
60°F	20 – 30
Ethylene Glycol/Hydrocarbon[8] Separators (Cold Separators)	20 – 60
Amine/Hydrocarbon Separators[9]	20 – 30
Coalescer, Hydrocarbon/Water Separators[9]	
100°F and above	5 – 10
80°F	10 – 20
60°F	20 – 30
Caustic/Propane	30 – 45
Caustic/Heavy Gasoline	30 – 90

Gas-Liquid-Liquid Separator Design

Liquid-liquid Settling Velocity (Based On Stokes Law) :

- The following equation can be used for calculating the settling velocity of water in oil or the upwards "settling" of oil in water. The important fact is to use the viscosity of the continuous phase i.e. : for oil settling upwards through water use the water viscosity, for water settling in oil use the oil viscosity.

$$U_t = \frac{g \, x D^2 (\rho_H - \rho_l)}{18 \, \mu_c}$$

U_t = terminal velocity m/s
g = gravitation acceleration m/s^2
ρ_H = density heavy fluid kg/m^3
ρ_l = density light fluid kg/m^3
μ_c = viscosity (continuous phase) kg/m.s
D = particle diameter m

- Setting the particle size to 125 microns and using more useful units gives :

$$U_t = 0.5108 \left(\frac{\rho_H - \rho_l}{\mu_c} \right)$$

U_t in mm/min
μ_c in centipoise
ρ in kg/m^3

- The above equation is valid for REYNOLDS number of 0.1 - 0.3.
- If calculated settling velocity is > 250 mm/min use 250 max.

Gas-Liquid-Liquid Separator Design

Horizontal 3-phase Separators sizing procedure (Total):

Sufficient residence time to allow separation of the oil-water mixture as well as the oil surge and vapour flow areas must be provided.

1. Proceed with steps 1 to 4 as for a two phase separation. Use *L / D = 3 (1st* estimate) and evaluate L.
2. Provision now has to be made to accommodate both oil and water surge volumes. Use Tan-Tan length L' and not nozzle-nozzle distance L.
3. Calculate LLL required to give approximate 4 min oil surge capacity (minimum). Inspection will reveal whether sufficient height exists below LLL to include the interface levels. If not, adjust the vessel D or L to give sufficient room.

- Note: If the water cut is very small, consideration may be given water boot instead of a baffle arrangement see step 10.

Gas-Liquid-Liquid Separator Design

Horizontal 3-phase Separators sizing procedure (Total):

4. Having determined HLL and LLL now set both position and height of baffle. Calculate terminal settling velocity of water droplet and settling time at both HLL and LLL ($U_{t,W}$ and $U_{t,L}$). Volumetric flow of liquid is in both cases the oil plus the water. Calculate fall distance of a droplet across length of the drum. Baffle height and position can now be set noting:

- the baffle should be at least 75 mm below the LLL.

- the baffle should be at least 2/3 down the length of the drum from the Inlet.

- in some cases the water droplets will settle to the floor in a short distance.

The baffle should still be set at a minimum of 2/3 along the vessel.

Horizontal velocity at HLL: $V_{HLL}=(Q_W+Q_L)/A_{HLL}$

Vertical fall from HLL $= B \times U_{t,W} / V_{HLL}$

HLL - Vertical fall from HLL should be less than baffle height.

Gas-Liquid-Liquid Separator Design

Horizontal 3-phase Separators sizing procedure (Total):

Horizontal velocity at LLL: $V_{LLL}=(Q_W+Q_L)/A_{LLL}$

Vertical fall from LLL $= B \times U_{t,W} / V_{LLL}$

LLL - Vertical fall from LLL should be less than baffle height.

5. Set the HIL at baffle height - 75 mm. The LIL according to height determined by vortex breaker + LSLL use a minimum of 300-350 mm.
6. Check If an oil droplet will rise through the water layer (from drum floor) to LLL before reaching water outlet. Use area at LLL with normal oil + water flowrates. (This criteria is very rarely governing but must be checked).

Horizontal velocity at LLL: $V_{LLL}=(Q_W+Q_L)/A_{LLL}$

Gas-Liquid-Liquid Separator Design

Horizontal 3-phase Separators sizing procedure (Total):

Vertical rise within distance B $= B \times U_{t,L} / V_{LLL}$

Vertical rise within distance B should be greater than baffle height.

7. Calculate water surge time between HIL and LIL, and residence time between NIL and outlet. Remember to use only one head volume, and length of drum up to baffle. Minimum acceptable times are 4-5 min. If calculated times are very long consider using a water boot arrangement.

8. Rationalise all dimensions and "tidy" levels to standard values if possible i.e: 150 mm, 200, 250, 300 etc. This allows use of standard displacers.

9. Recalculate all residence times based on "tidied" levels (if required).

   Note: In calculating the final residence times make sure that the vessel tan-tan length is used and not the nozzle to nozzle distance L.

Gas-Liquid-Liquid Separator Design

Horizontal 3-phase Separators sizing procedure (Total):

10. Boot Calculation

    If the water volumetric flow is so small as to not warrant a separate baffled settling compartment as detailed above a water boot should be used instead.

- To design proceed as follows:

1. Proceed as previous up to step 3.

2. Calculate settling distance of water droplet when vessel is operating at LLL. Water droplet should reach floor of drum before oil outlet. Remember that the oil exit nozzle will be raised above the floor as a standpipe. Adjust drum D or L to achieve settling.

3. Check that settling is also possible when operating at HLL. droplet to fall below drawoff nozzle level.

Gas-Liquid-Liquid Separator Design

Horizontal 3-phase Separators sizing procedure (Total):

4. Size water draw off boot diameter *(try to use standard pipe diameters).* Calculate rising velocity of the oil in water, set downward velocity of water In boot at 90% of this and evaluate boot diameter. Boot length by inspection (use standard displacers).

Note : Boot diameter must be less than 35% of vessel diameter.

Minimum diameter shall be 305 mm.

The height / diameter shall range from 2:1 to 5:1.

NOZZLE SIZING

- Inlet nozzle

- Size based on normal volumetric flow + 10 % (liquid + vapour flow).
- Limit inlet velocity to 7 - 13 m/s.
- Round nozzle diameter up or down to nearest standard size.

Gas-Liquid-Liquid Separator Design

Horizontal 3-phase Separators sizing procedure (Total):

NOZZLE SIZING

- Gas outlet

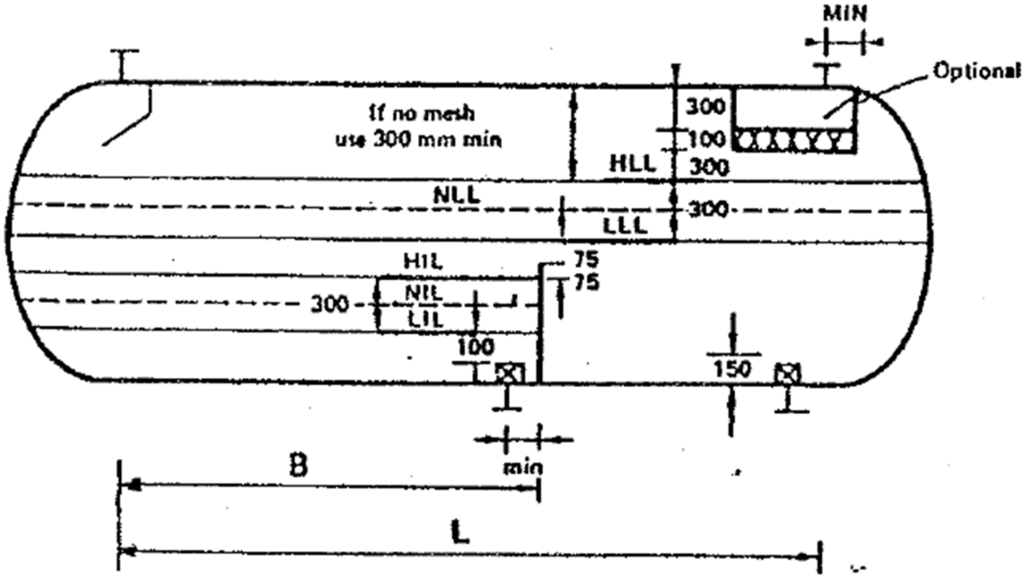
  - Size on normal flow
  - Velocity limit 15-30 m/s

- Liquid outlet

  - Normal flow + 10%
  - Velocity limit 1-3 m/s HC
    2-4 m/s water
  - Min. diameter = 2" (avoid plugging)

Gas-Liquid-Liquid Separator Design

Horizontal 3-phase Separators sizing procedure (Total):



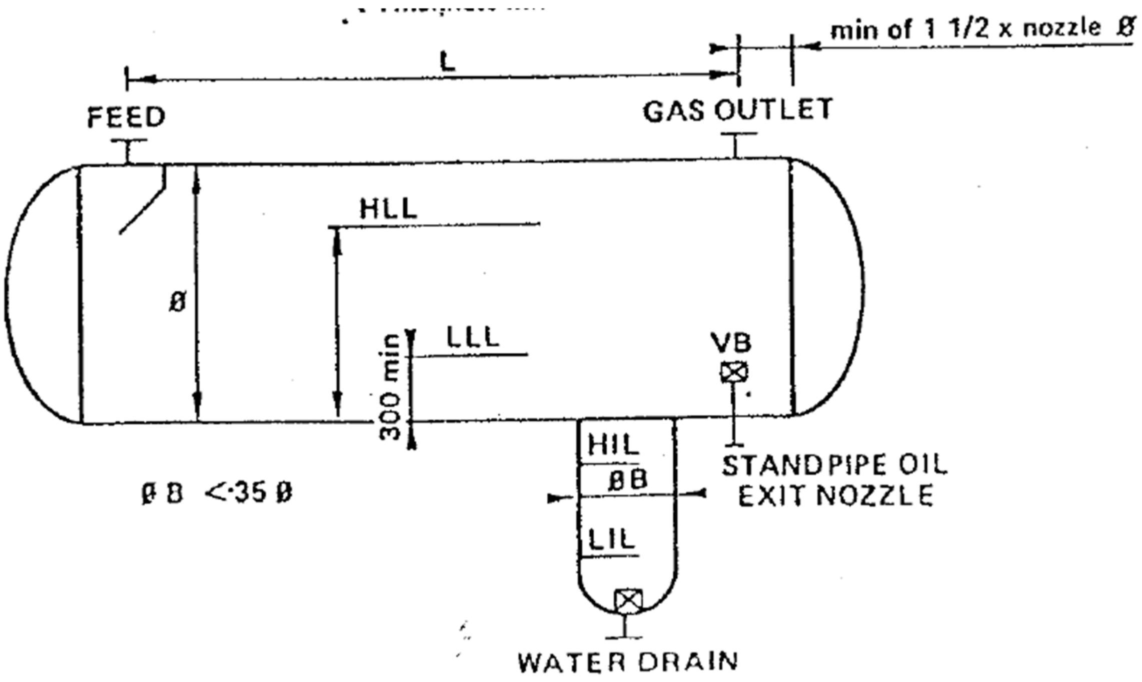
- OIL RESIDENCE TIME – Volume between NLL-NIL up to baffle only
  use residence time of 3-6 minutes for design

- OIL SURGE TIME - Volume between HLL and LLL across full length of vessel
  use 4-5 minutes if feeding to another column/vessel
  5 minutes if pumping to storage
  3 minutes if flowing to storage (no pump)
  8 minutes if sole charge to fired heater

Gas-Liquid-Liquid Separator Design

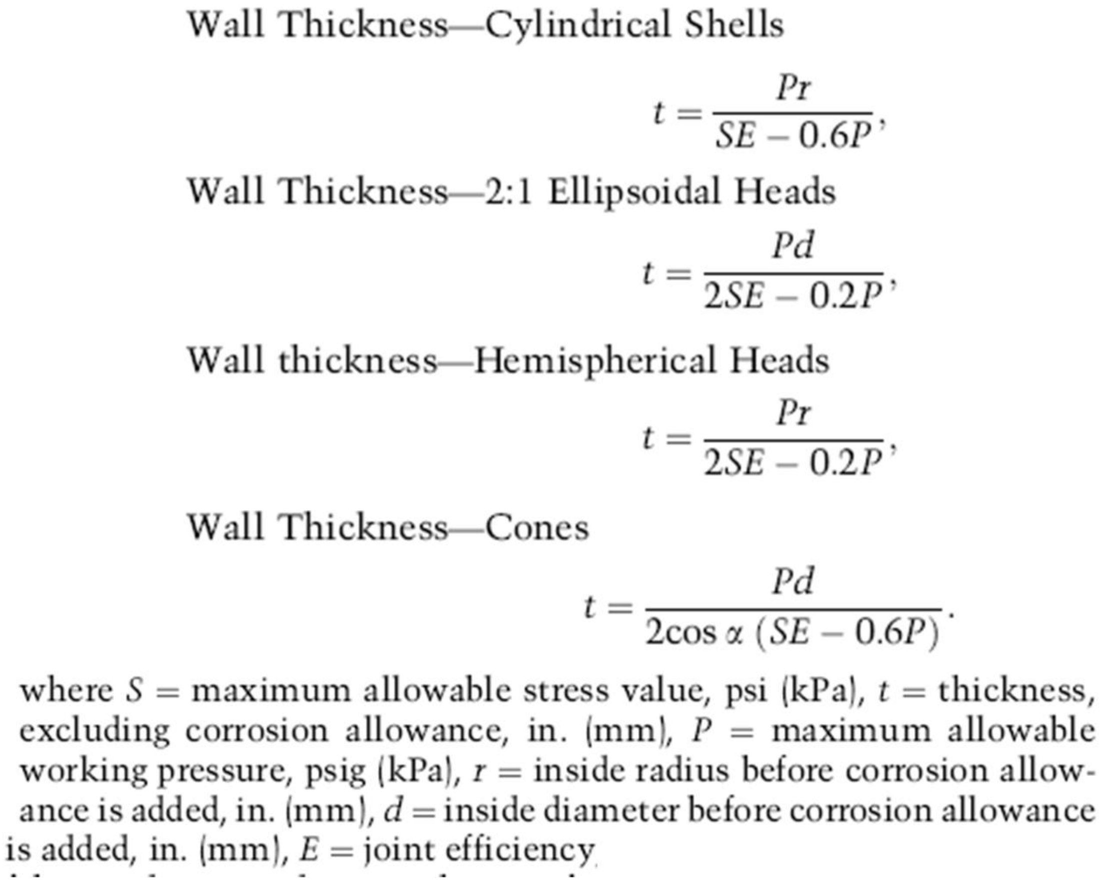
Horizontal 3-phase Separators sizing procedure (Total):

WATER RESIDENCE TIME -	Volume between NIL and outlet Use 4 minutes minimum
WATER SURGE TIME -	Volume between HIL and LIL Use 4-5 minutes minimum



Mechanical Design

- The following formulas are used in the ASME code Section VIII, Division 1 for determining wall thickness:



Wall Thickness—Cylindrical Shells

$$t = \frac{Pr}{SE - 0.6P},$$

Wall Thickness—2:1 Ellipsoidal Heads

$$t = \frac{Pd}{2SE - 0.2P},$$

Wall thickness—Hemispherical Heads

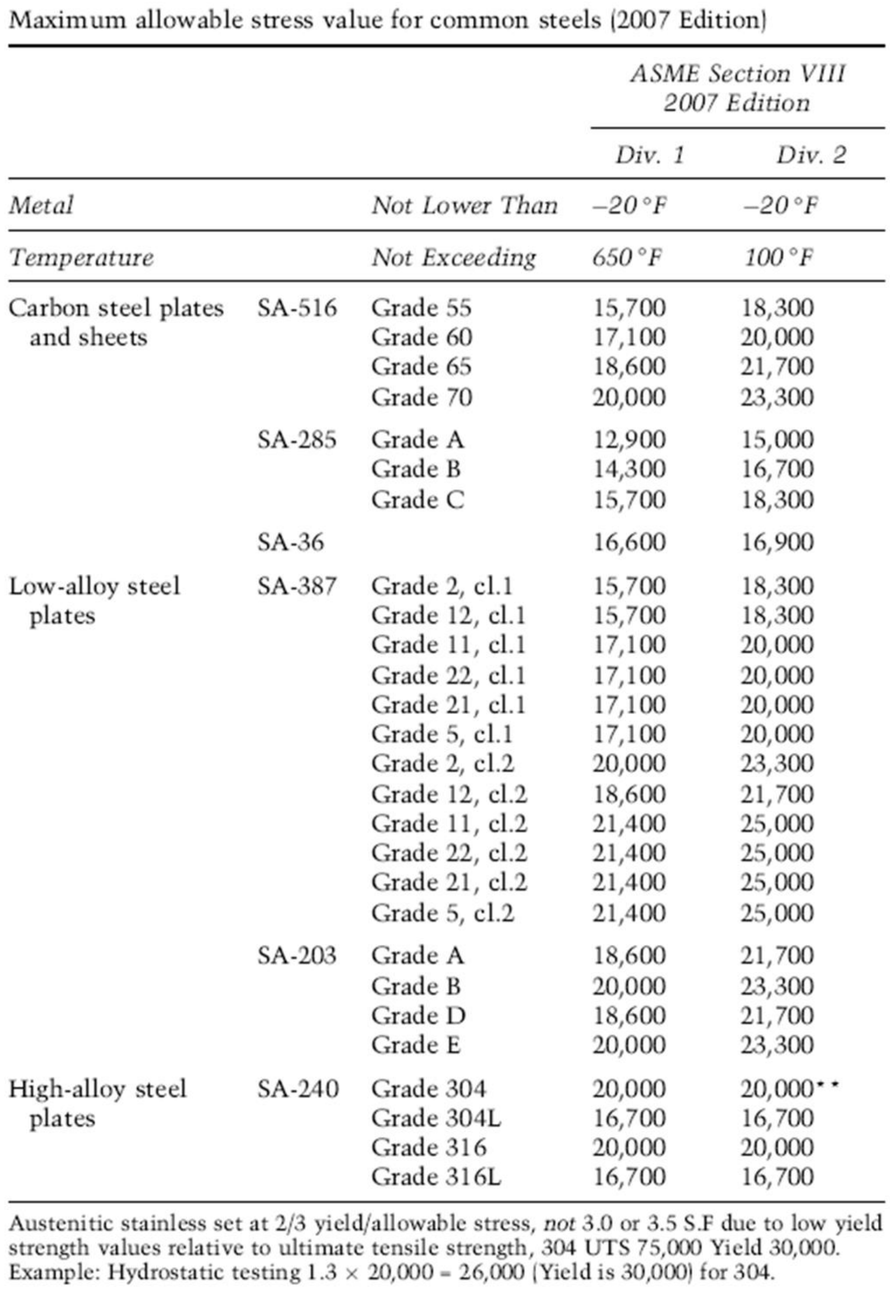
$$t = \frac{Pr}{2SE - 0.2P},$$

Wall Thickness—Cones

$$t = \frac{Pd}{2\cos\alpha\,(SE - 0.6P)}.$$

where S = maximum allowable stress value, psi (kPa), t = thickness, excluding corrosion allowance, in. (mm), P = maximum allowable working pressure, psig (kPa), r = inside radius before corrosion allowance is added, in. (mm), d = inside diameter before corrosion allowance is added, in. (mm), E = joint efficiency

Mechanical Design



Maximum allowable stress value for common steels (2007 Edition)

			ASME Section VIII 2007 Edition	
			Div. 1	*Div. 2*
Metal		*Not Lower Than*	*–20 °F*	*–20 °F*
Temperature		*Not Exceeding*	*650 °F*	*100 °F*
Carbon steel plates and sheets	SA-516	Grade 55	15,700	18,300
		Grade 60	17,100	20,000
		Grade 65	18,600	21,700
		Grade 70	20,000	23,300
	SA-285	Grade A	12,900	15,000
		Grade B	14,300	16,700
		Grade C	15,700	18,300
	SA-36		16,600	16,900
Low-alloy steel plates	SA-387	Grade 2, cl.1	15,700	18,300
		Grade 12, cl.1	15,700	18,300
		Grade 11, cl.1	17,100	20,000
		Grade 22, cl.1	17,100	20,000
		Grade 21, cl.1	17,100	20,000
		Grade 5, cl.1	17,100	20,000
		Grade 2, cl.2	20,000	23,300
		Grade 12, cl.2	18,600	21,700
		Grade 11, cl.2	21,400	25,000
		Grade 22, cl.2	21,400	25,000
		Grade 21, cl.2	21,400	25,000
		Grade 5, cl.2	21,400	25,000
	SA-203	Grade A	18,600	21,700
		Grade B	20,000	23,300
		Grade D	18,600	21,700
		Grade E	20,000	23,300
High-alloy steel plates	SA-240	Grade 304	20,000	20,000**
		Grade 304L	16,700	16,700
		Grade 316	20,000	20,000
		Grade 316L	16,700	16,700

Austenitic stainless set at 2/3 yield/allowable stress, *not* 3.0 or 3.5 S.F due to low yield strength values relative to ultimate tensile strength, 304 UTS 75,000 Yield 30,000. Example: Hydrostatic testing 1.3 × 20,000 = 26,000 (Yield is 30,000) for 304.

Mechanical Design

- The shell weight can be estimated from (SI) :

$$W = 0.0254\, dt\, L \qquad (5.5b)$$

where W = weight, lb (kg), d = internal diameter, in. (mm), t = wall thickness, in. (mm), L = shell length, ft (m).

- The weight of one 2:1 ellipsoidal head is approximately (SI):

$$W \approx 9.42 \times 10^{-6} td^2 + 1.34 \times 10^{-3} td$$

- The weight of nozzles and internals can be estimated at 5–10% of the sum of the shell and head weights.

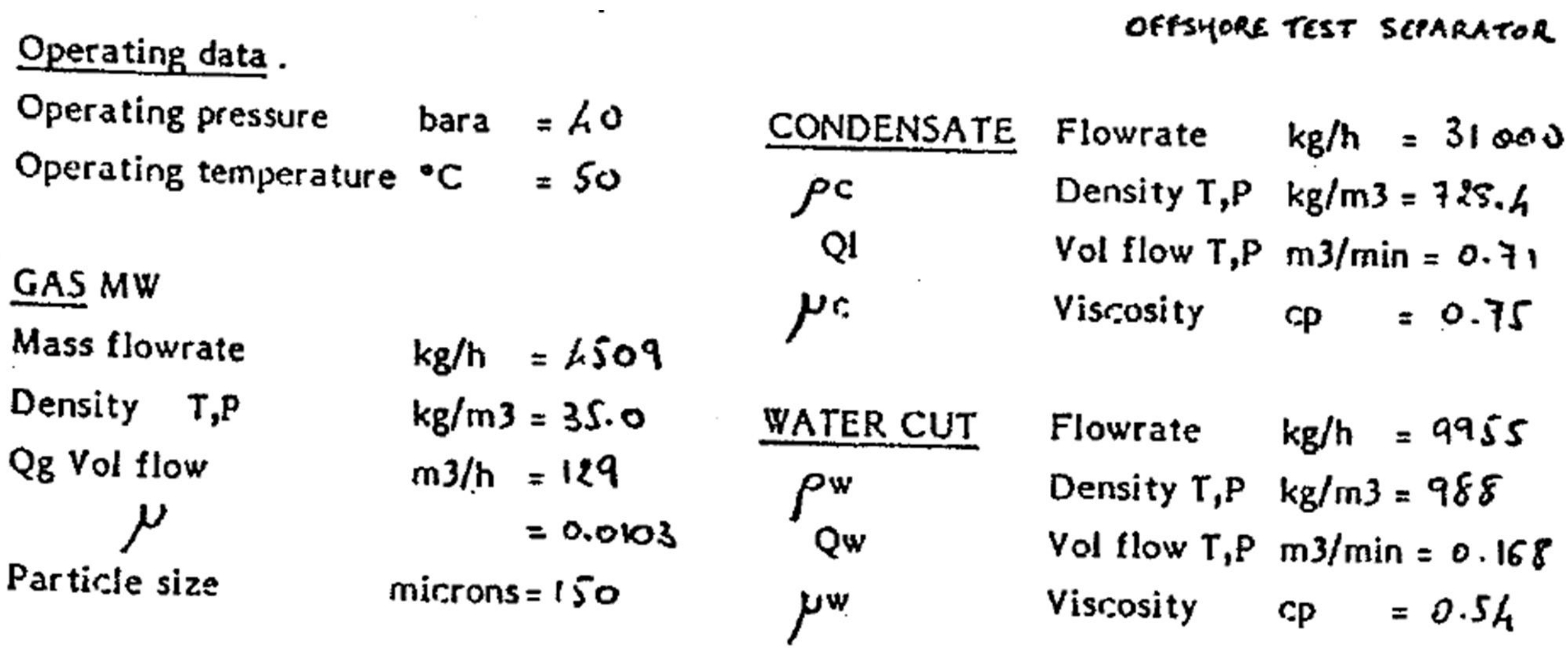
- The weight of pedestals for a horizontal vessel can be estimated as 10% of the total weight of the vessel.
- the weight of a skirt can be estimated as the same thickness as the shell (neglecting the corrosion allowance) with a length given by (SI) :

$L = 2.5 \times 10^{-4} d + 0.61$ where L = skirt length in ft (m)

References

- Engineering Data book , Gas Processors Suppliers Association (GPSA), 2004
- Specification for Oil and Gas Separators, API SPEC 12J
- ASME Section VIII Div 1
- Gas-Liquid and Liquid-Liquid Separators, K.Arnold, M.Stewart, Gulf pub. Company, 2008

Exercise



OFFSHORE TEST SEPARATOR

Operating data .

Operating pressure bara = 40

Operating temperature °C = 50

GAS MW

Mass flowrate kg/h = 4509

Density T,P kg/m3 = 35.0

Qg Vol flow m3/h = 129

μ = 0.0103

Particle size microns = 150

CONDENSATE

Flowrate kg/h = 31000

ρ^c Density T,P kg/m3 = 725.4

Ql Vol flow T,P m3/min = 0.71

μ^c Viscosity cp = 0.75

WATER CUT

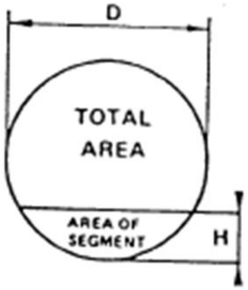
Flowrate kg/h = 9955

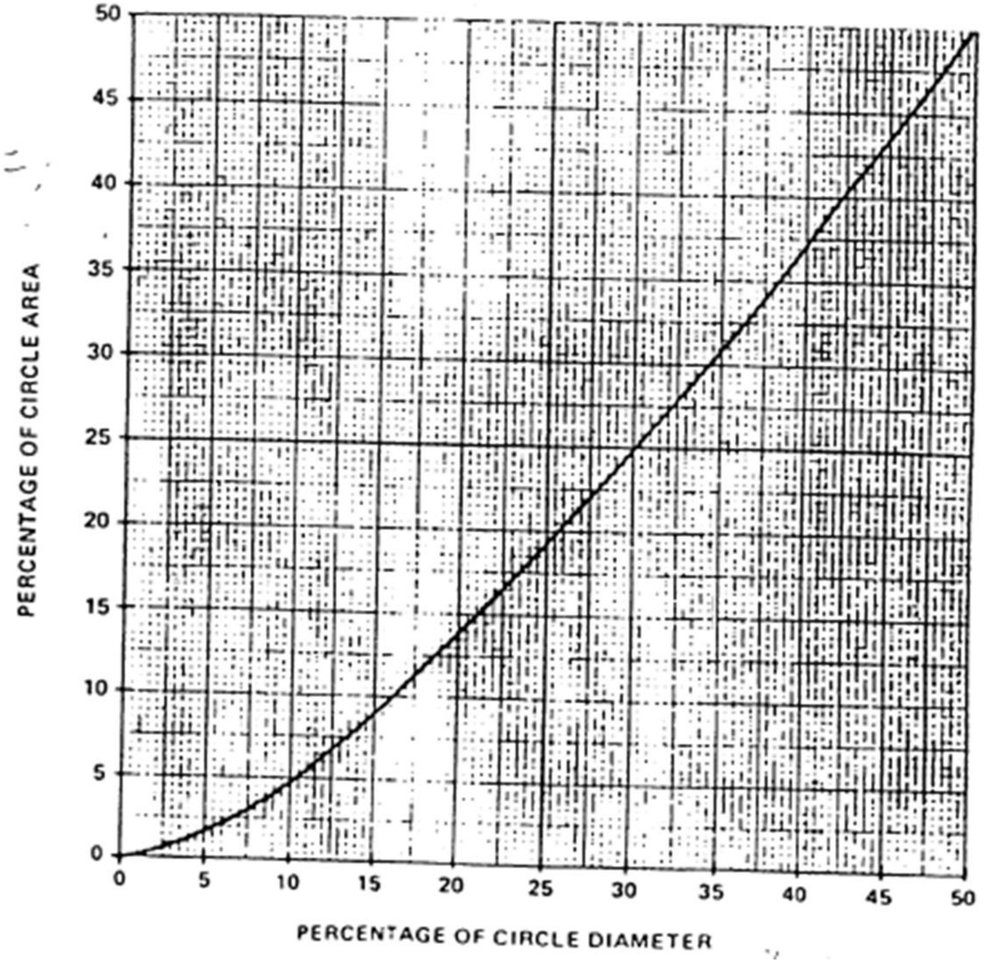
ρ^w Density T,P kg/m3 = 988

Qw Vol flow T,P m3/min = 0.168

μ^w Viscosity cp = 0.54

Gas-Liquid Separator Design





Gas-Liquid-Liquid Separator Design

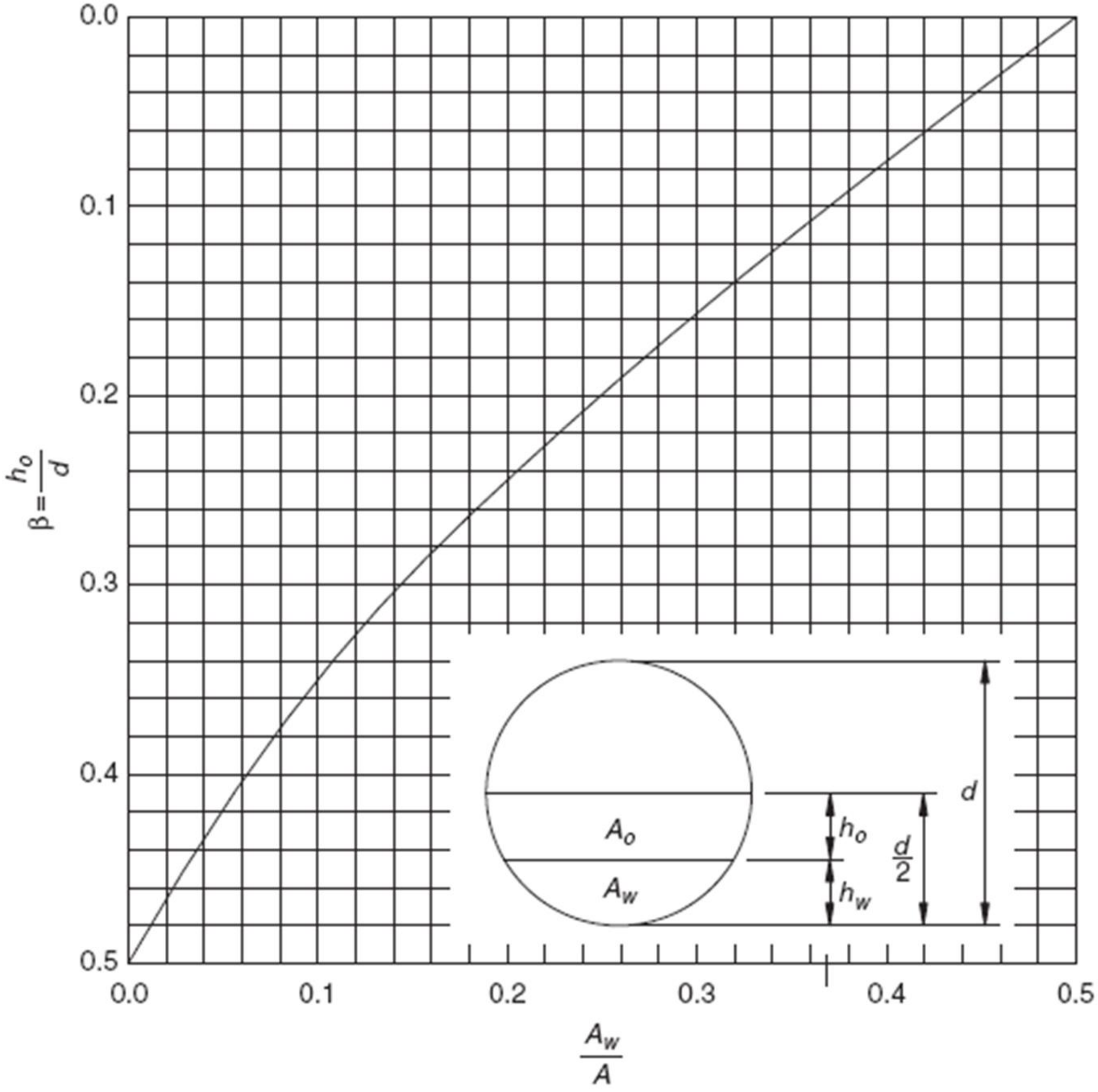


FIGURE 4.20. Coefficient "β" for a cylinder half filled with liquid.