SECTION 7

Separators and Filters

PRINCIPLES OF SEPARATION

Three principles used to achieve physical separation of gas and liquids or solids are momentum, gravity settling, and coalescing. Any separator may employ one or more of these principles, but the fluid phases must be "immiscible" and have different densities for separation to occur.

FIG. 7-1

Nomenclature

- A = area, ft^2
- A_p = particle or droplet cross sectional area, ft^2
- C = empirical constant for separator sizing, ft/hr
- C^* = empirical constant for liquid-liquid separators, $(bbl \cdot cp)/(ft^2 \cdot day)$
- C' = drag coefficient of particle, dimensionless (Fig. 7-3)
- D_i = separator inlet nozzle diameter, in.
- D_p = droplet diameter, ft
- D_v = inside diameter of vessel, ft
- G_m = maximum allowable gas mass-velocity necessary for particles of size D_p to drop or settle out of gas, $lb/(hr \cdot ft^2)$
- g = acceleration due to gravity, 32.2 ft/sec^2
- H_l = width of liquid interface area, ft
- J = gas momentum, $lb/(ft \cdot sec^2)$
- K = empirical constant for separator sizing, ft/sec
- K_{CR} = proportionality constant from Fig. 7-4 for use in Eq 7-5, dimensionless
- L = seam to seam length of vessel, ft
- L_l = length of liquid interface area, ft
- M = mass flow, lb/sec
- M_p = mass of droplet or particle, lb
- MW = molecular weight, lb/lb mole
- P = system pressure, psia
- Q = estimated gas flow capacity, MMscfd per ft^2 of filter area
- Q_A = actual gas flow rate, ft^3/sec
- R = gas constant, 10.73 $(psia \cdot ft^3)/(°R \cdot lb\ mole)$
- Re = Reynolds number, dimensionless
- S_{hl} = specific gravity of heavy liquid, water = 1.0
- S_{ll} = specific gravity of light liquid, water = 1.0
- T = system temperature, °R
- t = retention time, minutes
- U = volume of settling section, bbl
- V_t = critical or terminal gas velocity necessary for particles of size D_p to drop or settle out of gas, ft/sec
- W = total liquid flow rate, bbl/day
- W_{cl} = flow rate of light condensate liquid, bbl/day
- Z = compressibility factor, dimensionless

Greek:

- ρ_g = gas phase density, lb/ft^3
- ρ_l = liquid phase density, droplet or particle, lb/ft^3
- μ = viscosity of continuous phase, cp

Filter Separators: A filter separator usually has two compartments. The first compartment contains filter-coalescing elements. As the gas flows through the elements, the liquid particles coalesce into larger droplets and when the droplets reach sufficient size, the gas flow causes them to flow out of the filter elements into the center core. The particles are then carried into the second compartment of the vessel (containing a vane-type or knitted wire mesh mist extractor) where the larger droplets are removed. A lower barrel or boot may be used for surge or storage of the removed liquid.

Flash Tank: A vessel used to separate the gas evolved from liquid flashed from a higher pressure to a lower pressure.

Line Drip: Typically used in pipelines with very high gas-to-liquid ratios to remove only free liquid from a gas stream, and not necessarily all the liquid. Line drips provide a place for free liquids to separate and accumulate.

Liquid-Liquid Separators: Two immiscible liquid phases can be separated using the same principles as for gas and liquid separators. Liquid-liquid separators are fundamentally the same as gas-liquid separators except that they must be designed for much lower velocities. Because the difference in density between two liquids is less than between gas and liquid, separation is more difficult.

Scrubber or Knockout: A vessel designed to handle streams with high gas-to-liquid ratios. The liquid is generally entrained as mist in the gas or is free-flowing along the pipe wall. These vessels usually have a small liquid collection section. The terms are often used interchangeably.

Separator: A vessel used to separate a mixed-phase stream into gas and liquid phases that are "relatively" free of each other. Other terms used are scrubbers, knockouts, line-drips, and decanters.

Slug Catcher: A particular separator design able to absorb sustained in-flow of large liquid volumes at irregular intervals. Usually found on gas gathering systems or other two-phase pipeline systems. A slug catcher may be a single large vessel or a manifolded system of pipes.

Three Phase Separator: A vessel used to separate gas and two immiscible liquids of different densities (e.g. gas, water, and oil).

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 the heavier phase to turn as rapidly as the lighter fluid, so separation occurs. Momentum is usually employed for bulk separation of the two phases in a stream.

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 (see Fig. 7-2). These forces can be described mathematically using the terminal or free settling velocity.

$$V_t = \sqrt{\frac{2\,g\,M_p\,(\rho_l - \rho_g)}{\rho_l\,\rho_g\,A_p\,C'}} = \sqrt{\frac{4\,g\,D_p\,(\rho_l - \rho_g)}{3\,\rho_g\,C'}} \qquad \textbf{Eq 7-1}$$

The drag coefficient has been found to be a function of the shape of the particle and the Reynolds number of the flowing gas. For the purpose of this equation particle shape is considered to be a solid, rigid sphere.

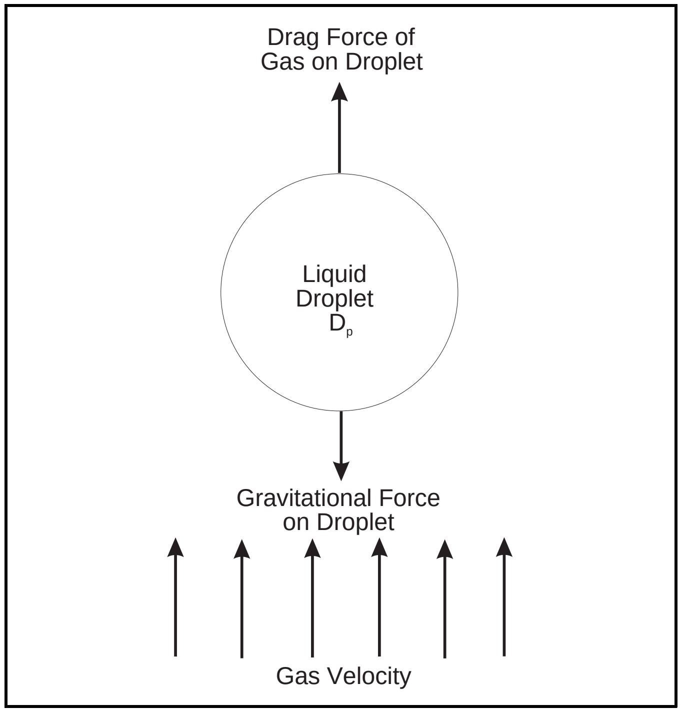
Reynolds number is defined as:

$$Re = \frac{1{,}488\,D_p\,V_t\,\rho_g}{\mu} \qquad \textbf{Eq 7-2}$$

In this form, a trial and error solution is required since both particle size, D_p, and terminal velocity, V_t, are involved. To avoid trial and error, values of the drag coefficient are presented in Fig. 7-3 as a function of the product of drag coefficient, C′, times the Reynolds number squared; this technique eliminates velocity from the expression[1]. The abscissa of Fig. 7-3 is given by:

FIG. 7-2

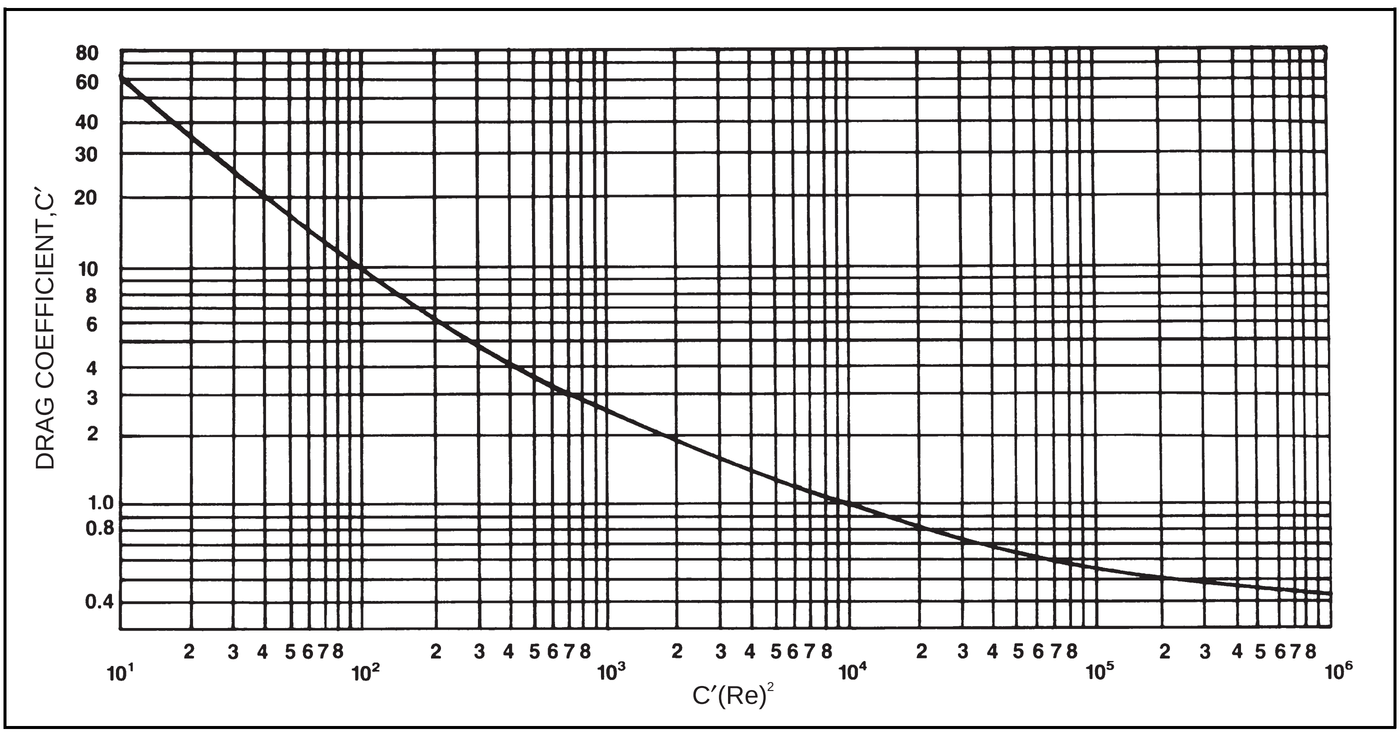
Forces on Liquid Droplet in Gas Stream



$$C'\,(Re)^2 = \frac{(0.95)\,(10^8)\,\rho_g\,D_p^3\,(\rho_l - \rho_g)}{\mu^2} \qquad \textbf{Eq 7-3}$$

FIG. 7-3

Drag Coefficient of Rigid Spheres[13]



Gravity Settling – Limiting Conditions

As with other fluid flow phenomena, the drag coefficient reaches a limiting value at high Reynolds numbers.

Newton's Law—For relatively larger particles (approximately 1000 microns and larger) the gravity settling is described by Newton's law (Fig. 7-4). The limiting drag coefficient is 0.44 at Reynolds numbers above about 500. Substituting C′ = 0.44 in Eq 7-1 produces the Newton's law equation expressed as:

$$V_t = 1.74 \sqrt{\frac{g\, D_p\, (\rho_l - \rho_g)}{\rho_g}} \qquad \textbf{Eq 7-4}$$

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. The maximum droplet which can settle out can be determined by:

$$D_p = K_{CR}\left[\frac{\mu^2}{g\, \rho_g\, (\rho_l - \rho_g)}\right]^{0.33} \qquad \textbf{Eq 7-5}$$

For the Newton's law region, the upper limit to Reynolds number is 200,000 and K_{CR} = 18.13.

Stokes' Law—At low Reynolds numbers (less than 2), a linear relationship exists between drag coefficient and the Reynolds number (corresponding to laminar flow). Stokes' law applies in this case and Eq 7-1 can be expressed as:

$$V_t = \frac{1{,}488\, g\, D_p^2\, (\rho_l - \rho_g)}{18\, \mu} \qquad \textbf{Eq 7-6}$$

The droplet diameter corresponding to a Reynolds number of 2 can be found using a value of 0.0080 for K_{CR} in Eq 7-5.

The lower limit for Stokes' law applicability is a droplet diameter of approximately 3 microns. The upper limit is about 100 microns.

A summary of these equations is presented in Fig. 7-4.

Coalescing

Very small droplets such as fog or mist cannot be separated practically by gravity. These droplets can be coalesced to form larger droplets that will settle by gravity. Coalescing devices in separators force gas to follow a tortuous path. The momentum of the droplets causes them to collide with other droplets or the coalescing device, forming larger droplets. These larger droplets can then settle out of the gas phase by gravity. Wire mesh screens, vane elements, and filter cartridges are typical examples of coalescing devices.

SEPARATOR DESIGN AND CONSTRUCTION

Separators are usually characterized as vertical, horizontal, or spherical. Horizontal separators can be single or double barrel and can be equipped with sumps or boots.

Parts of a Separator

Regardless of shape, separation vessels usually contain four major sections, plus the necessary controls. These sections are shown for horizontal and vertical vessels in Fig. 7-5. The primary separation section, A, is used to separate the main portion of free liquid in the inlet stream. It contains the inlet nozzle which may be tangential, or a diverter baffle to take advantage of the inertial effects of centrifugal force or an abrupt change of direction to separate the major portion of the liquid from the gas stream.

The secondary or gravity section, B, is designed to utilize the force of gravity to enhance separation of entrained droplets. It consists of a portion of the vessel through which the gas moves at a relatively low velocity with little turbulence. In some designs, straightening vanes are used to reduce turbulence. The vanes also act as droplet collectors, and reduce the distance a droplet must fall to be removed from the gas stream.

The coalescing section, C, utilizes a coalescer or mist extractor which can consist of a series of vanes, a knitted wire mesh pad, or cyclonic passages. This section removes the very small droplets of liquid from the gas by impingement on a surface where they coalesce. A typical liquid carryover from the mist extractor is less than 0.1 gallon per MMscf.

The sump or liquid collection section, D, acts as receiver for all liquid removed from the gas in the primary, secondary, and coalescing sections. Depending on requirements, the liquid section should have a certain amount of surge volume, for degassing or slug catching, over a minimum liquid level necessary for controls to function properly. Degassing may require a horizontal separator with a shallow liquid level while emulsion separation may also require higher temperature, higher liquid level, and/or the addition of a surfactant.

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?

Vertical Separators

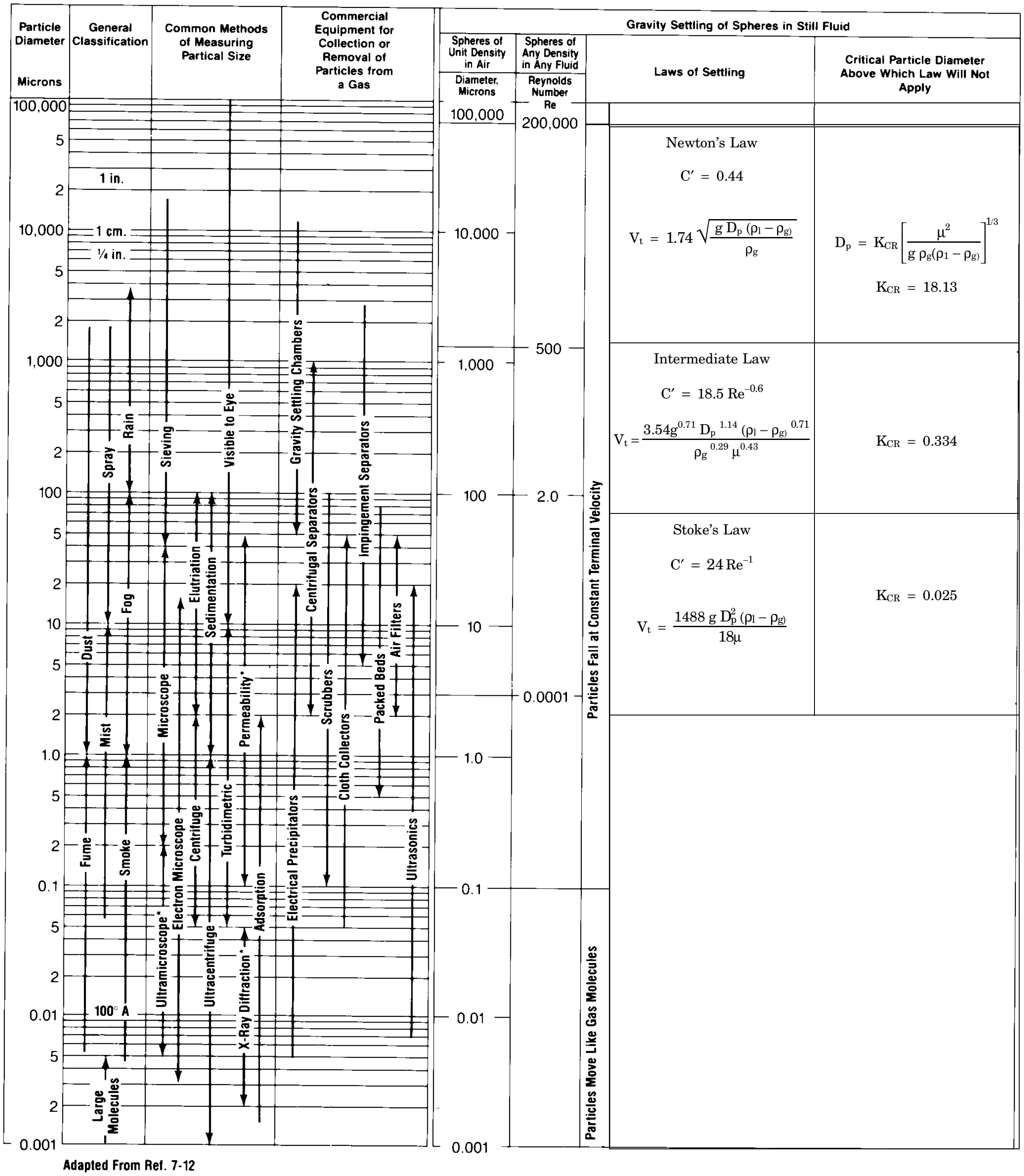
Vertical separators, Fig. 7-6, are usually selected when the gas-liquid ratio is high or total gas volumes are low. In the vertical separator, the fluids enter the vessel striking a diverting baffle which initiates primary separation. Liquid removed by the inlet baffle falls to the bottom of the vessel. The gas moves upward, usually passing through a mist extractor to remove suspended mist, and then the "dry" gas flows out. Liquid removed by the mist extractor is coalesced into larger droplets which then fall through the gas to the liquid reservoir in the bottom. The ability to handle liquid slugs is typically obtained by increasing height. 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.

As an example of a vertical separator, consider a compressor suction scrubber. In this service the vertical separator:

- Does not need significant liquid retention volume.

FIG. 7-4

Gravity Settling Laws and Particle Characteristics



Adapted From Ref. 7-12

FIG. 7-5

Gas-Liquid Separators

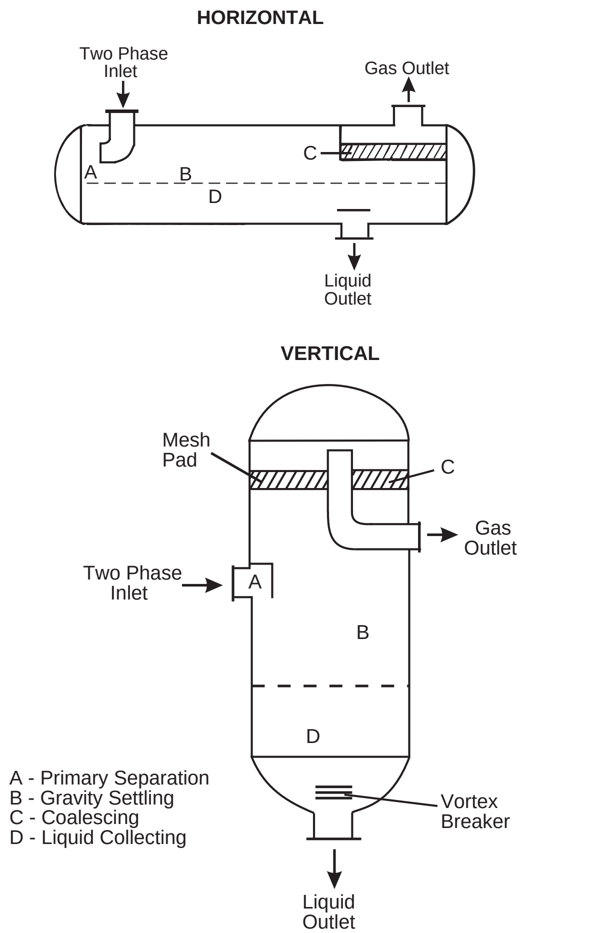
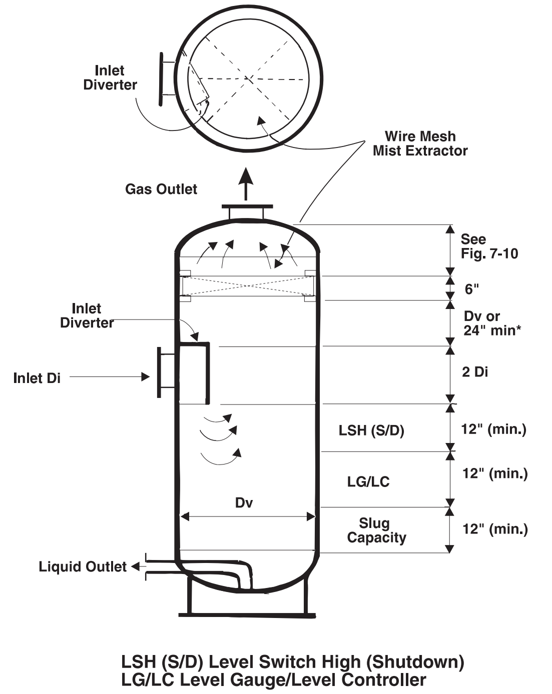


FIG. 7-6

Example Vertical Separator with Wire Mesh Mist Extractor



- Dimensions may be influenced by instrument connection requirements.
- For small diameter separators (≤ 48" ID.) with high L/G inlet flow ratios this dimension should be increased by as much as 50%.
- May use syphon type drain to:
  - A. reduce vortex possibility
  - B. reduce external piping that requires heating (freeze protection)

- The liquid level responds quickly to any liquid that enters—thus tripping an alarm or shutdown.
- The separator occupies a small amount of plot space.

Horizontal Separators

Horizontal separators are most efficient where large volumes of total fluids and large amounts of dissolved gas are present with the liquid. The greater liquid surface area in this configuration provides optimum conditions for releasing entrapped gas. In the horizontal separator, Fig. 7-7, the liquid which has been separated from the gas moves along the bottom of the vessel to the liquid outlet. The gas and liquid occupy their proportionate shares of shell cross-section. Increased slug capacity is obtained through shortened retention time and increased liquid level. Fig. 7-7 also illustrates the separation of two liquid phases (glycol and hydrocarbon). The denser glycol settles to the bottom and is withdrawn through the "boot." The glycol level is controlled by a conventional level control instrument.

In a double barrel separator, the liquids fall through connecting flow pipes into the external liquid reservoir below. Slightly smaller vessels may be possible with the double barrel horizontal separator where surge capacity establishes the size of the lower liquid collection chamber.

As an example of a horizontal separator consider a rich amine flash tank. In this service:

- There is relatively large liquid surge volume leading to longer retention time (this allows more complete release of the dissolved gas and, if necessary, surge volume for the circulating system).
- There is more surface area per liquid volume to aid in more complete degassing.
- The horizontal configuration would handle a foaming liquid better than a vertical.
- The liquid level responds slowly to changes in liquid inventory.

Spherical Separators

These separators are occasionally used for high pressure service where compact size is desired and liquid volumes are small. Fig. 7-8 is a schematic for an example spherical separator. Factors considered for a spherical separator are:

- compactness;
- limited liquid surge capacity;
- minimum steel for a given pressure.

FIG. 7-7

Example Horizontal Three-Phase Separator with Wire Mesh Mist Extractor

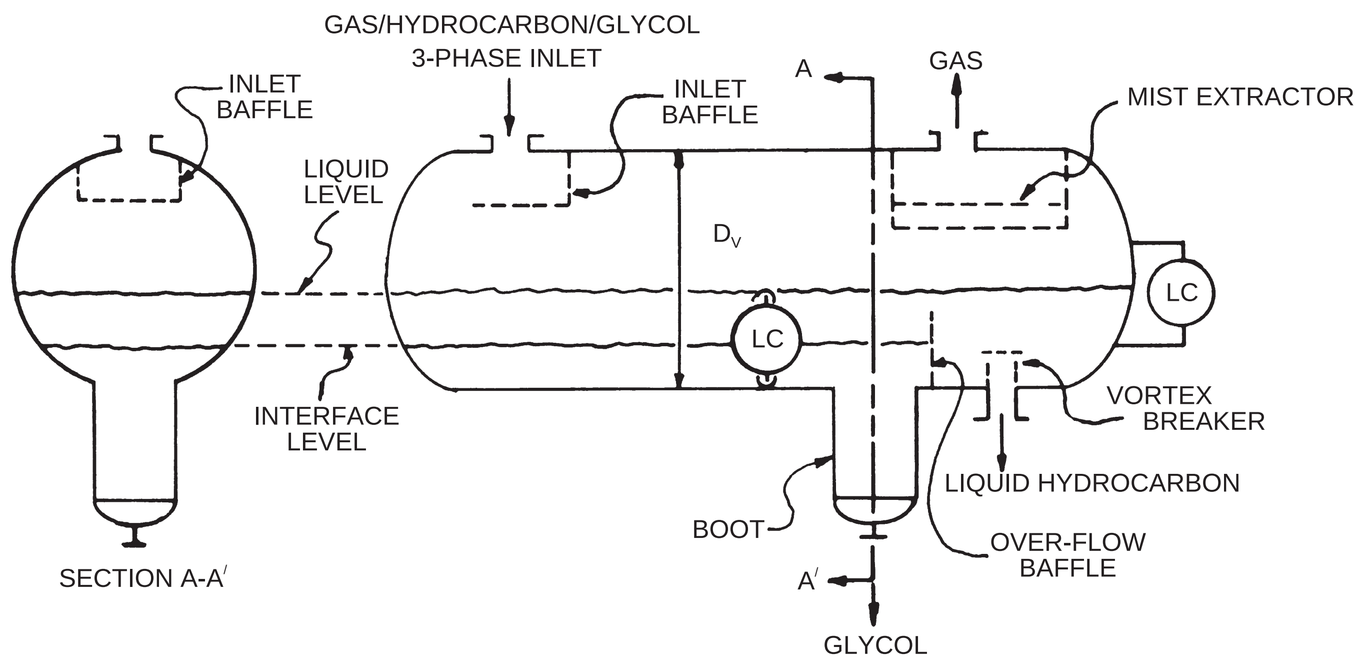
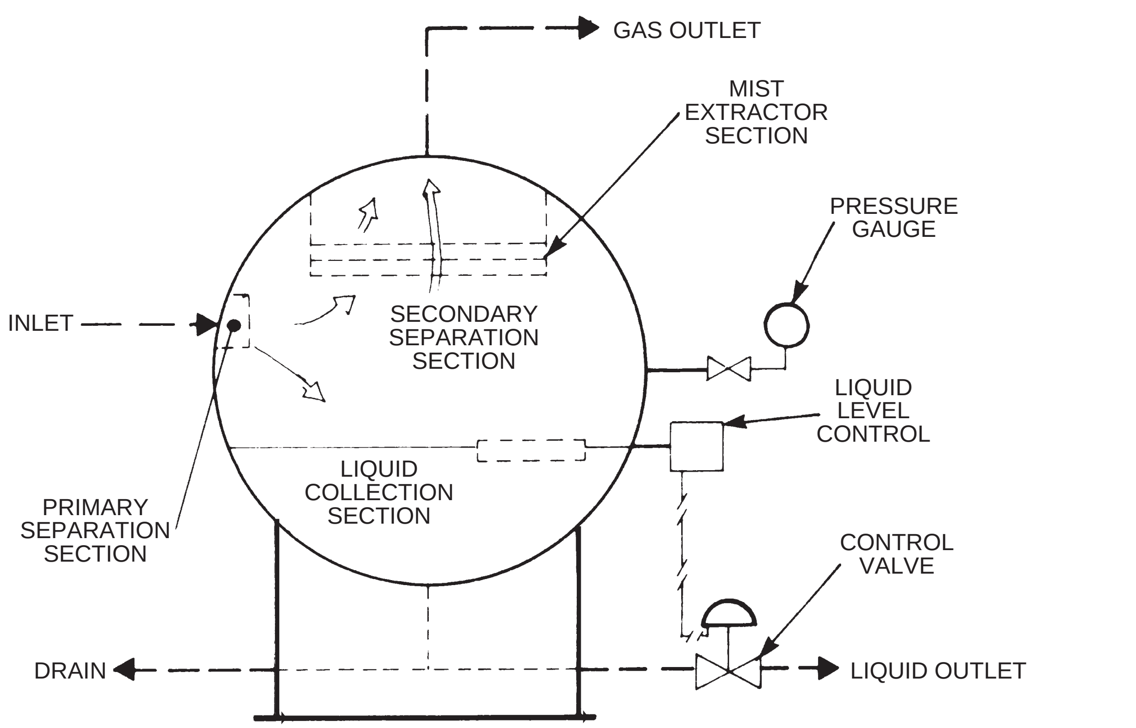


FIG. 7-8

Example Spherical Separator[3]



Courtesy American Petroleum Institute

GAS-LIQUID SEPARATOR DESIGN

Specifying Separators

Separator designers need to know pressure, temperature, flow rates, and physical properties of the streams as well as the degree of separation required. It is also prudent to define if these conditions all occur at the same time or if there are only certain combinations that can exist at any time. If known, the type and amount of liquid should also be given, and whether it is mist, free liquid, or slugs.

For example, a compressor suction scrubber designed for 70-150 MMscfd gas at 400-600 psig and 65-105°F would require the separator manufacturer to offer a unit sized for the worst conditions, i.e., 150 MMscfd at 400 psig and 105°F. But the real throughput of the compressor varies from 150 MMscfd at 600 psig, 105°F to 70 MMscfd at 400 psig, 65°F. Because the high volume only occurs at the high pressure, a smaller separator is acceptable. Conversely, a pipeline separator could be just the opposite because of winter to summer flow changes.

Basic Design Equations

Separators without mist extractors are designed for gravity settling using Eq 7-1. Values for the drag coefficient are given in Fig. 7-3 for spherical droplet particles. Typically the sizing is based upon removal of 150 micron diameter droplets.

Most vertical separators that employ mist extractors are sized using equations that are derived from Eq 7-1. The two most common are the critical velocity equation:

$$V_t = K\sqrt{\frac{\rho_l - \rho_g}{\rho_g}} \qquad \textbf{Eq 7-7}$$

and the correlation developed by Souders and Brown[2] to relate vessel diameter to the velocity of rising vapors which will not entrain sufficient liquid to cause excessive carryover:

$$G_m = C\sqrt{\rho_g(\rho_l - \rho_g)} \qquad \textbf{Eq 7-8}$$

Note that if both sides of Eq 7-7 are multiplied by gas density, it is identical to Eq 7-8 when:

$$C = 3600\ K \qquad \textbf{Eq 7-9}$$

Some typical values of the separator sizing factors, K and C, are given in Fig.7-9. Separators are sized using these equations to calculate vessel cross-sectional areas that allow gas velocities at or below the gas velocities calculated by Eq 7-7 or 7-8.

Horizontal separators greater than 10 ft. in length with mist extractors are sized using Eqs 7-10 and 7-11[3]. Horizontal separators less than 10 ft. in length should use Eqs 7-7 and 7-8. In horizontal separators, the gas drag force does not directly oppose the gravitational settling force. The true droplet velocity is assumed to be the vector sum of the vertical terminal velocity and the horizontal gas velocity. Hence, the minimum length of the vessel is calculated by assuming the time for the gas to flow from the inlet to the outlet is the same as the time for the droplet to fall from the top of the vessel to the surface of the liquid. In calculating the gas capacity of horizontal separators, the cross-sectional area of that portion of the vessel occupied by liquid (at maximum level) is subtracted from the total vessel cross-sectional area. Separators can be any length, but the ratio of seam-to-seam length to the diameter of the vessel, L/D_v, is usually in the range of 2:1 to 4:1.

FIG. 7-9

Typical K & C Factors for Sizing Woven Wire Demisters

Separator Type	K Factor (ft/sec)	C Factor (ft/hr)
Horizontal	0.40 to 0.50	1440 to 1800
Vertical	0.18 to 0.35	650 to 1260
Spherical	0.20 to 0.35	720 to 1260
Wet Steam	0.25	900
Most vapors under vacuum	0.20	720
Salt & Caustic Evaporators	0.15	540
Adjustment of K & C Factor for Pressure - % of design value[15]		
Atmospheric	100	
150 psi	90	
300 psi	85	
600 psi	80	
1150 psi	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

$$V_t = K\sqrt{\frac{\rho_l - \rho_g}{\rho_g}}\left(\frac{L}{10}\right)^{0.56} \qquad \textbf{Eq 7-10}$$

$$G_m = C\sqrt{\rho_g(\rho_l - \rho_g)}\left(\frac{L}{10}\right)^{0.56} \qquad \textbf{Eq 7-11}$$

Frequently separators without mist extractors are sized using Eq 7-7 and 7-8 with a constant (K or C) of typically one-half of that used for vessels with mist extractors. Although combining the drag coefficient and other physical properties into an empirical constant is unsound, it can be justified since:

- Selection of the droplet diameter (separation efficiency) is arbitrary. Even if the diameter can be selected on a rational basis, little information is available on the mass distribution above and below the selected size.
- Liquid droplets are not rigid spherical particles in dilute concentration (unhindered settling).

Note: A number of the "separator" sizing equations given only size the separation *element* (mist extractor, Eqs 7-7, 7-8, 7-10, 7-11, and vane separator, Eq 7-13): these equations *do not* directly size the actual separator containment *vessel*.

Thus, for example, a 24 in. diameter wire mesh mist extractor might be installed in a 36 in. diameter vessel because the liquid surge requirements dictated a larger vessel.

Separators without Mist Extractors

This is typically a horizontal vessel which utilizes gravity as the sole mechanism for separating the liquid and gas phases. Gas and liquid enter through the inlet nozzle and are slowed to a velocity such that the liquid droplets can fall out of the gas phase. The dry gas passes into the outlet nozzle and the liquid is drained from the lower section of the vessel.

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 (one micron is 10^{-4} cm or 0.00003937 inch).

The length of vessel required can then be calculated by assuming that the time for the gas to flow from inlet to outlet is the same as the time for the liquid droplet of size D_p to fall from the top of the vessel to the liquid surface. Eq 7-12 then relates the length of the separator to its diameter as a function of this settling velocity (assuming no liquid retention):

$$L = \frac{4\,Q_A}{\pi\,V_t\,D_v} \qquad \textbf{Eq 7-12}$$

If the separator is to be additionally used for liquid storage, this must also be considered in sizing the vessel.

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 0.50. It is desired to remove all entrainment greater than 150 microns in diameter. No liquid surge is required.

Gas density, $\rho_g = \frac{P\,(MW)}{RTZ} = \frac{(514.7)\,(21.72)}{(10.73)\,(560)\,(0.90)}$

$= 2.07 \text{ lb/ft}^3$

Liquid density, $\rho_l = 0.5\,(62.4) = 31.2 \text{ lb/ft}^3$

Mass flow, $M = \frac{(60)\,(10^6)\,(21.72)}{(379)\,(24)\,(3600)} = 39.8 \text{ lb/sec}$

Particle diameter, $D_p = \frac{(150)\,(0.00003937)}{12} = 0.000492 \text{ ft}$

From Eq 7-3,

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

$$= \frac{(0.95)\,(10^8)\,(2.07)\,(0.000492)^3\,(31.2 - 2.07)}{(0.012)^2}$$

$$= 4738$$

From Fig. 7-3, Drag coefficient, $C' = 1.40$

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

$$= \sqrt{\frac{4\,(32.2)\,(0.000492)\,(29.13)}{3\,(2.07)\,1.40}}$$

$$= \sqrt{0.212} = 0.46 \text{ ft/sec}$$

Gas flow, $Q_A = \frac{M}{\rho_g} = \frac{39.80}{2.07} = 19.2 \text{ ft}^3\text{/sec}$

Assume a diameter, $D_v = 3.5$ ft

Vessel length, $L = \frac{4\,Q_A}{\pi\,V_t\,D_V} = \frac{4\,(19.2)}{\pi\,(0.46)\,(3.5)}$

$= 15.2$ ft

Other reasonable solutions are as follows:

Diameter, ft.	Length, ft.
3.5	15.2
4.0	13.3
4.5	11.8
5.0	10.6

Usually vessels up through 24 in. diameter have nominal pipe dimensions while larger vessels are rolled from plate with 6 in. internal increments in diameter.

Example 7-2—What size vertical separator without mist extractor is required to meet the conditions used in Example 7-1?

$$A = \frac{Q_A}{V_t} = \frac{19.2}{0.46} = 41.7 \text{ ft}^2$$

$D_v = 7.29$ ft minimum; use 90 inch ID

Separators With Wire Mesh Mist Extractors

Wire mesh pads are frequently used as entrainment separators for the removal of very small liquid droplets and, therefore, a higher overall percentage removal of liquid. Removal of droplets down to 10 microns or smaller may be possible with these pads. The pad is generally horizontal with the gas and entrained liquid passing vertically upward. Performance is adversely affected if the pad is tilted more than 30 degrees from the horizontal[4]. Liquid droplets impinge on the mesh pad, coalesce, and fall downward through the rising gas stream. Wire mesh pads are efficient only when the gas stream velocity is low enough that re-entrainment of the coalesced droplets does not occur. Figs. 7-10 and 7-11 illustrate a typical wire mesh installation in vertical and horizontal vessels.

Eqs 7-7 and 7-10 define the maximum gas velocity as a function of the gas density and the liquid density. A value for K can be found from Fig. 7-9. Firmly secure the top and bottom of the pad so that it is not dislodged by high gas flows, such as when a pressure relief valve lifts.

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 six inch thick pad with 9 to 12 lb/ft^3 bulk density. Minimum recommended pad thickness is four inches[4]. Manufacturers should be contacted for specific designs.

Wire mesh pads can be used in horizontal vessels. A typical installation is shown in Fig. 7-11. The preferred orientation of the mesh pad is in the horizontal plane. When installed in a vertical orientation, the pad is reported to be less efficient. Problems have been encountered where liquid flow through the pad to the sump is impaired due to dirt or sludge accumulation causing a higher liquid level on one side, providing the serious potential of the pad being dislodged from its mounting brackets making it useless, or forcing parts of it into the outlet pipe. The retaining frame must be designed to hold the mist pad in place during emergency blowdown or other periods of anticipated high vapor velocity.

The pressure drop across a wire mesh pad is sufficiently low (usually less than an inch of water) to be considered negligible for most applications. The effect of the pressure drop becomes significant only in the design of vacuum services and for equipment where the prime mover is a blower or a fan. Manufacturers should be contacted for specific information.

FIG. 7-10

Example Minimum Clearance — Mesh Type Mist Eliminators

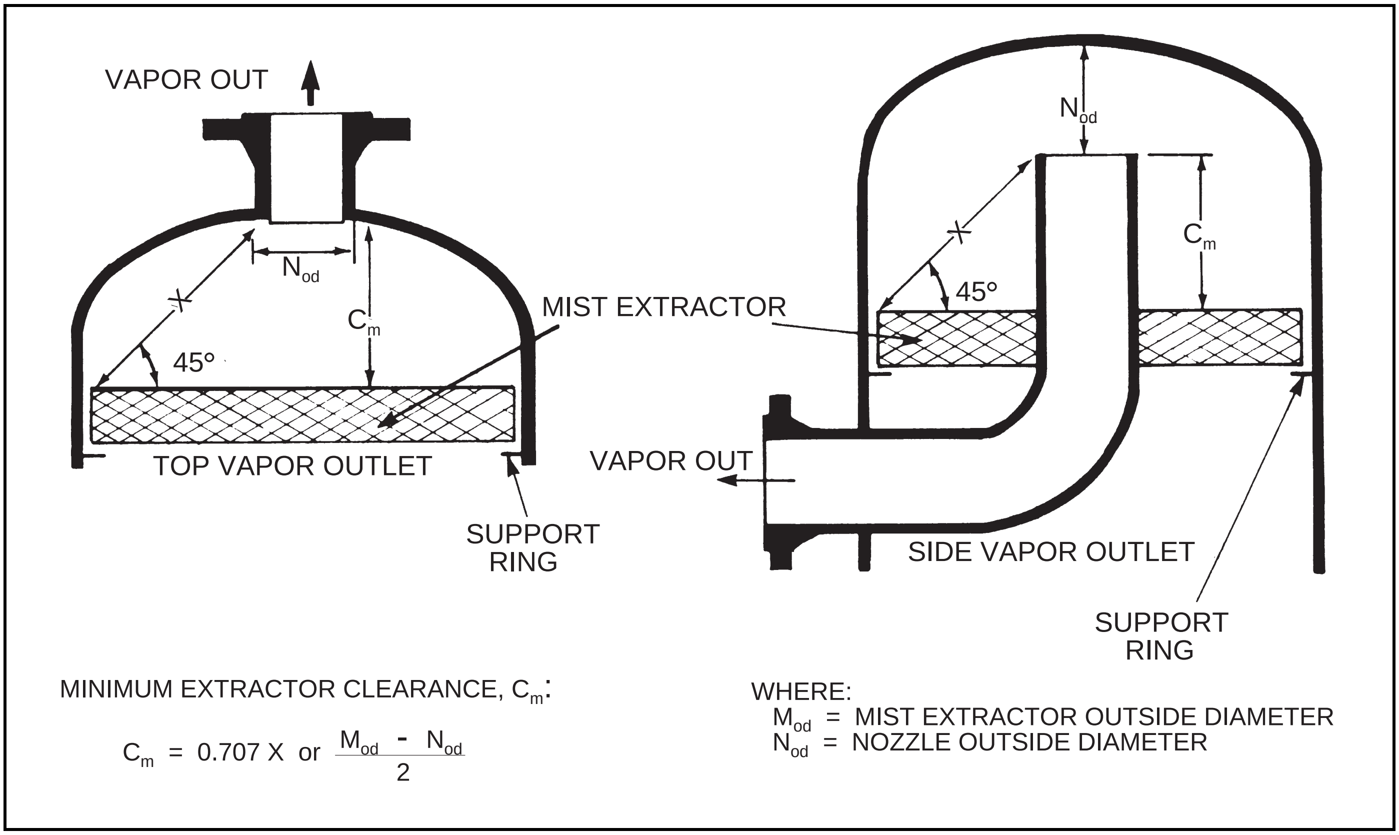
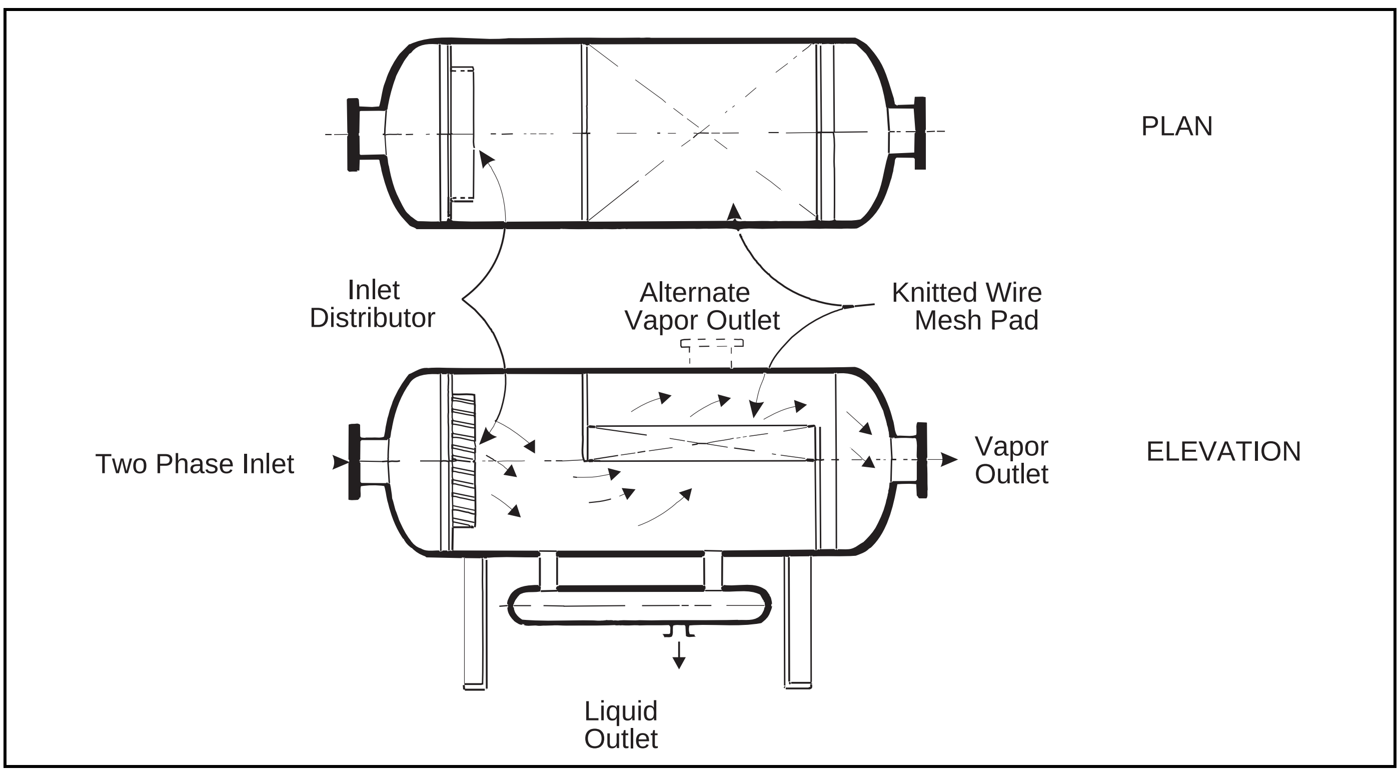


FIG. 7-11

Horizontal Separator with Knitted Wire Mesh Pad Mist Extractor and Lower Liquid Barrel



Example 7-3 — What size vertical separator equipped with a wire mesh mist extractor is required for the conditions used in Examples 7-1 and 7-2?

$$K = 0.28 \text{ ft/sec (from Fig. 7-9 for 500 psig)}$$

$$V_t = 0.28\sqrt{\frac{31.2 - 2.07}{2.07}} = 1.05 \text{ ft/sec}$$

$$A = \frac{Q_A}{V_t} = \frac{19.2}{1.05} = 18.3 \text{ ft}^2$$

$$D_v = 4.82 \text{ ft minimum; use 60 in. ID vessel}$$

Separators with Vane Type Mist Extractors

Vanes differ from wire mesh in that they do not drain the separated liquid back through the rising gas stream. Rather, the liquid can be routed into a downcomer, which carries the fluid directly to the liquid reservoir. A vertical separator with a typical vane mist extractor is shown in Fig. 7-12.

The vanes remove fluid from the gas stream by directing the flow through a torturous path. A cross-section of a typical vane unit is shown in Fig. 7-13. The liquid droplets, being heavier than the gas, are subjected to inertial forces which throw them against the walls of the vane. This fluid is then drained by gravity from the vane elements into a downcomer.

Vane type separators generally are considered to achieve the same separation performance as wire mesh, with the added advantage that they do not readily plug and can often be housed in smaller vessels. As vane type separators depend upon inertial forces for performance, turndown can sometimes be a problem.

Vane type separator designs are proprietary and are not easily designed with standard equations. Manufacturers of vane type separators should be consulted for detailed designs of their specific equipment. However, a gas momentum equation[5] can be used to estimate the approximate face area of a vane type mist extractor similar to that illustrated in Fig. 7-13.

$$J = \rho_g V_t^2 = 20 \text{ lb/(ft} \cdot \text{sec}^2) \qquad \textbf{Eq 7-13}$$

where gas velocity, V_t, is the velocity through the extractor cross-section.

Separators with Centrifugal Elements

There are several types of centrifugal separators which serve to separate solids as well as liquids from a gas stream. These devices are proprietary and cannot be readily sized without detailed knowledge of the characteristics of the specific internals. The manufacturer of such devices should be consulted for assistance in sizing these types of separators. Use care in selecting a unit as some styles are not suitable in some applications. A typical centrifugal separator is shown in Fig. 7-14. The main advantage of a centrifugal separator over a filter (or filter separator) is that much less maintenance is involved. Disadvantages of centrifugal separators are:

- some designs do not handle slugs well,
- efficiency is not as good as other types of separators,
- pressure drop tends to be higher than vane or clean knitted mesh mist extractors, and
- they have a narrow operating flow range for highest efficiency.

FIG. 7-12

Example Vertical Separator with Vane Type Mist Extractor

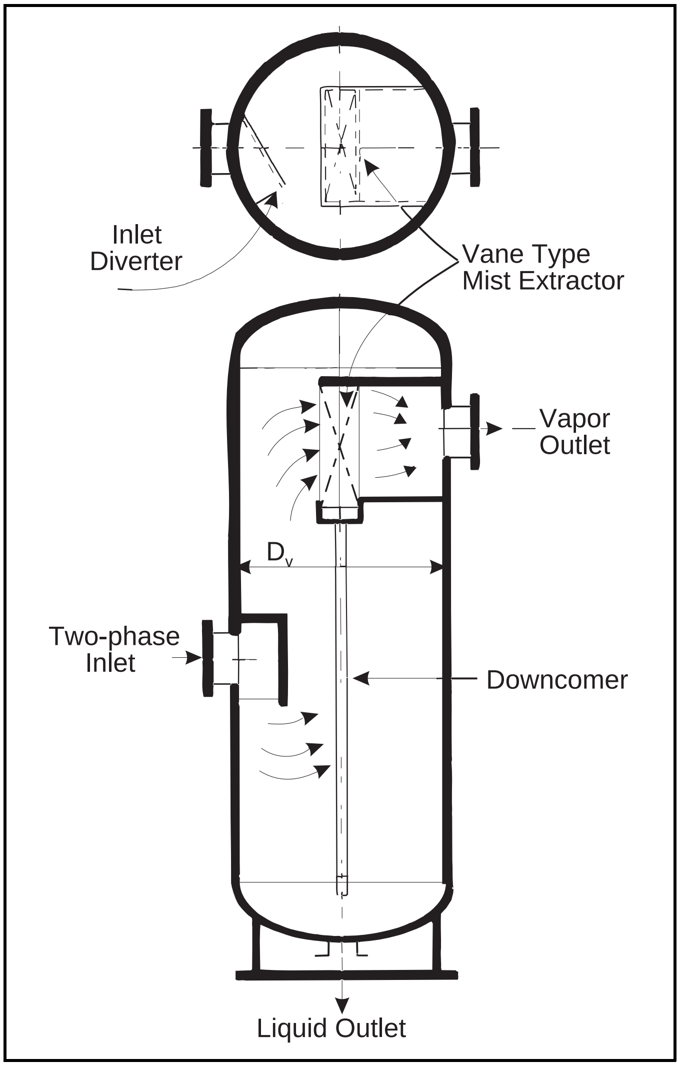


FIG. 7-13

Cross Section of Example Vane Element Mist Extractor Showing Corrugated Plates with Liquid Drainage Traps

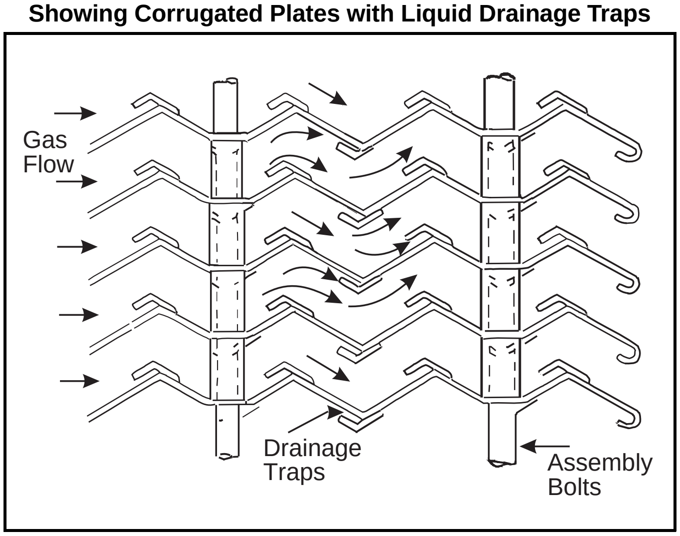
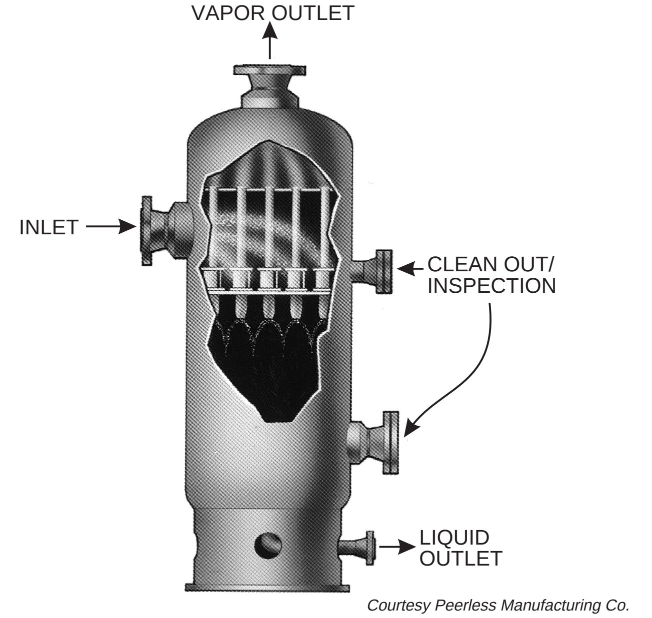


FIG. 7-14

Example Vertical Separator with Centrifugal Elements



Filter Separators

General — This type of separator has a higher separation efficiency than the centrifugal separator, but it uses filter elements, which must periodically be replaced. An example filter separator is shown in Fig. 7-15. Gas enters the inlet nozzle and passes through the filter section where solid particles are filtered from the gas stream and liquid particles are coalesced into larger droplets. These droplets pass through the tube and are entrained into the second section of the separator, where a final mist extraction element removes these coalesced droplets from the gas stream.

The design of filter separators is proprietary and a manufacturer should be consulted for specific size and recommendations. The body size of a horizontal filter separator for a typical application can be estimated by using 1.3 for the value of K in Eq 7-7. This provides an approximate body diameter for a unit designed to remove water (other variables such as viscosity and surface tension enter into the actual size determination). Units designed for water will be smaller than units sized to remove light hydrocarbons.

Example 7-4 — A filter separator is required to handle a flow of 60 MMscfd at conditions presented in Example 7-1. Estimate the diameter of a filter separator.

$$V_t = 1.3\sqrt{\frac{31.2 - 2.07}{2.07}} = 4.88 \text{ ft/sec}$$

$$A = \frac{Q_A}{V_t} = \frac{19.2}{4.88} = 3.93 \text{ ft}^2$$

$$D_v = 2.2 \text{ ft} = 26.9 \text{ in. minimum}$$

Use 30 inch ID separator.

In many cases the vessel size will be determined by the filtration section rather than the mist extraction section. The filter cartridges coalesce the liquid mist into droplets which can be easily removed by the mist extractor section. A design consideration commonly overlooked is the velocity out of these filter tubes into the mist extraction section. If the velocity is too high, the droplets will be sheared back into a fine mist that will pass through the extractor element. A maximum allowable velocity for gas exiting the filter tube attachment pipe can be estimated using the momentum Eq 7-13 with a value of 1250 for J. Light hydrocarbon liquids or low pressure gas should be limited to even less than this value. No published data can be cited since this information is proprietary with each filter separator manufacturer.

Design — The most common and efficient agglomerator is composed of a tubular fiber glass filter pack which is capable of holding the liquid particles through submicron sizes. Gas flows into the top of the filter pack, passes through the elements and then travels out through the tubes. Small, dry solid particles are retained in the filter elements and the liquid coalesces to form larger particles. Liquid agglomerated in the filter pack is then removed by a mist extractor located near the gas outlet.

The approximate filter surface area for gas filters can be estimated from Fig. 7-16. The figure is based on applications such as molecular sieve dehydrator outlet gas filters. For dirty gas service the estimated area should be increased by a factor of two or three.

The efficiency of a filter separator largely depends on the proper design of the filter pack, i.e., a minimum pressure drop while retaining an acceptable extraction efficiency. A pressure drop of approximately 1-2 psi is normal in a clean filter separator. If excessive solid particles are present, it may be necessary to clean or replace the filters at regular intervals when a pressure drop in excess of 10 psi is observed. However, as a rule, 25 psi is recommended as a maximum as the cartridge units might otherwise collapse. Removal of the filter pack is easily achieved by using a quick-opening closure.

Various guarantees are available from filter separator manufacturers such as one for 100 percent removal of liquid droplets 8 microns and larger and 99.5 percent removal of particles in the 0.5-8 micron range. However, guarantees for the performance of separators and filters are very difficult to verify in the field.

While most dry solid particles about ten microns and larger are removable, the removal efficiency is about 99 percent for particles below approximately ten microns.

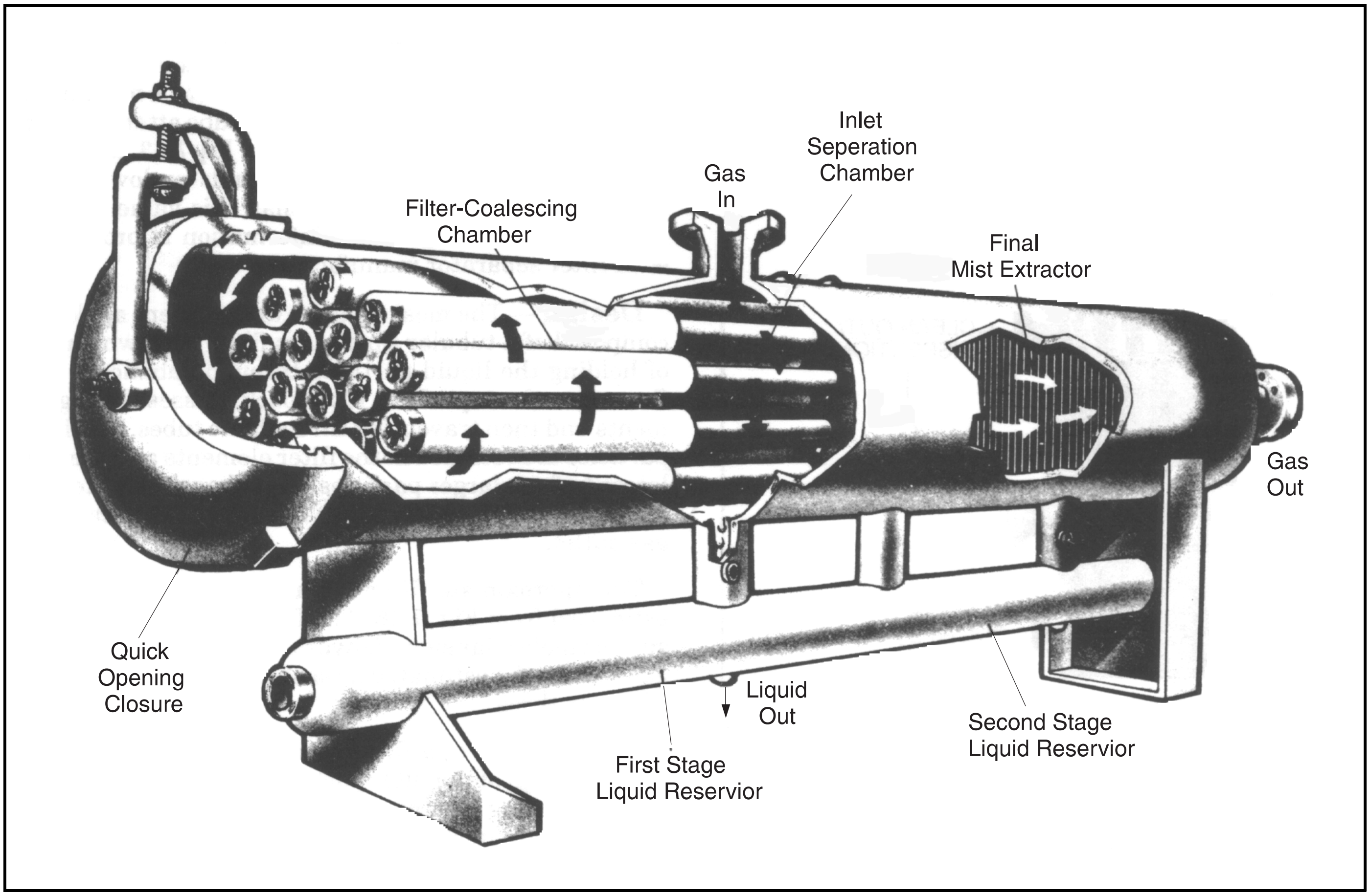
For heavy liquid loads, or where free liquids are contained in the inlet stream, a horizontal filter separator with a liquid sump, which collects and dumps the inlet free-liquids separately from coalesced liquids, is often preferred.

LIQUID-LIQUID SEPARATOR DESIGN

Liquid-liquid separation may be divided into two broad categories of operation. The first is defined as "gravity separation" where the two immiscible liquid phases separate within the vessel by the differences in density of the liquids. Sufficient retention time must be provided in the separator to allow for the gravity separation to take place. The second category is defined as "coalescing separation." This is where small particles of one liquid phase must be separated or removed from a large quantity of another liquid phase. Different types of internal construction of separators must be provided for each type of liquid-liquid separation. The following principles of de-

FIG. 7-15

Example Horizontal Filter-Separator



sign for liquid-liquid separation apply equally for horizontal or vertical type separators. Horizontal vessels have some advantage over vertical ones for liquid-liquid separation, due to the larger interface area available in the horizontal style, and the shorter distance particles must travel to coalesce.

There are two factors which may prevent two liquid phases from separating due to differences in specific gravity:

- If droplet particles are so small they may be suspended by Brownian movement. This is defined as a random motion which is greater than directed movement due to gravity for particles less than 0.1 micron in diameter.
- The droplets may carry electric charges due to dissolved ions, and these charges can cause the droplets to repel each other rather than coalesce into larger particles and settle by gravity.

Effects due to Brownian movement are usually small and proper chemical treatment will usually neutralize any electric charges. Then settling becomes a function of gravity and viscosity in accordance with Stokes' law. The settling velocity of spheres through a fluid is directly proportional to the difference in densities of the sphere and the fluid, and inversely proportional to the viscosity of the fluid and the square of the diameter of the sphere (droplet), Eq 7-6. The liquid-liquid separation capacity of separators may be determined[8] from Eqs 7-14 and 7-15 which were derived from Eq 7-6. Values of C* are found in Fig. 7-17.

Vertical Vessels:

$$W_{cl} = C^* \left(\frac{S_{hl} - S_{ll}}{\mu}\right)(0.785)\, D_v^2 \qquad \textbf{Eq 7-14}$$

Horizontal Vessels:

$$W_{cl} = C^* \left(\frac{S_{hl} - S_{ll}}{\mu}\right) L_l\, H_l \qquad \textbf{Eq 7-15}$$

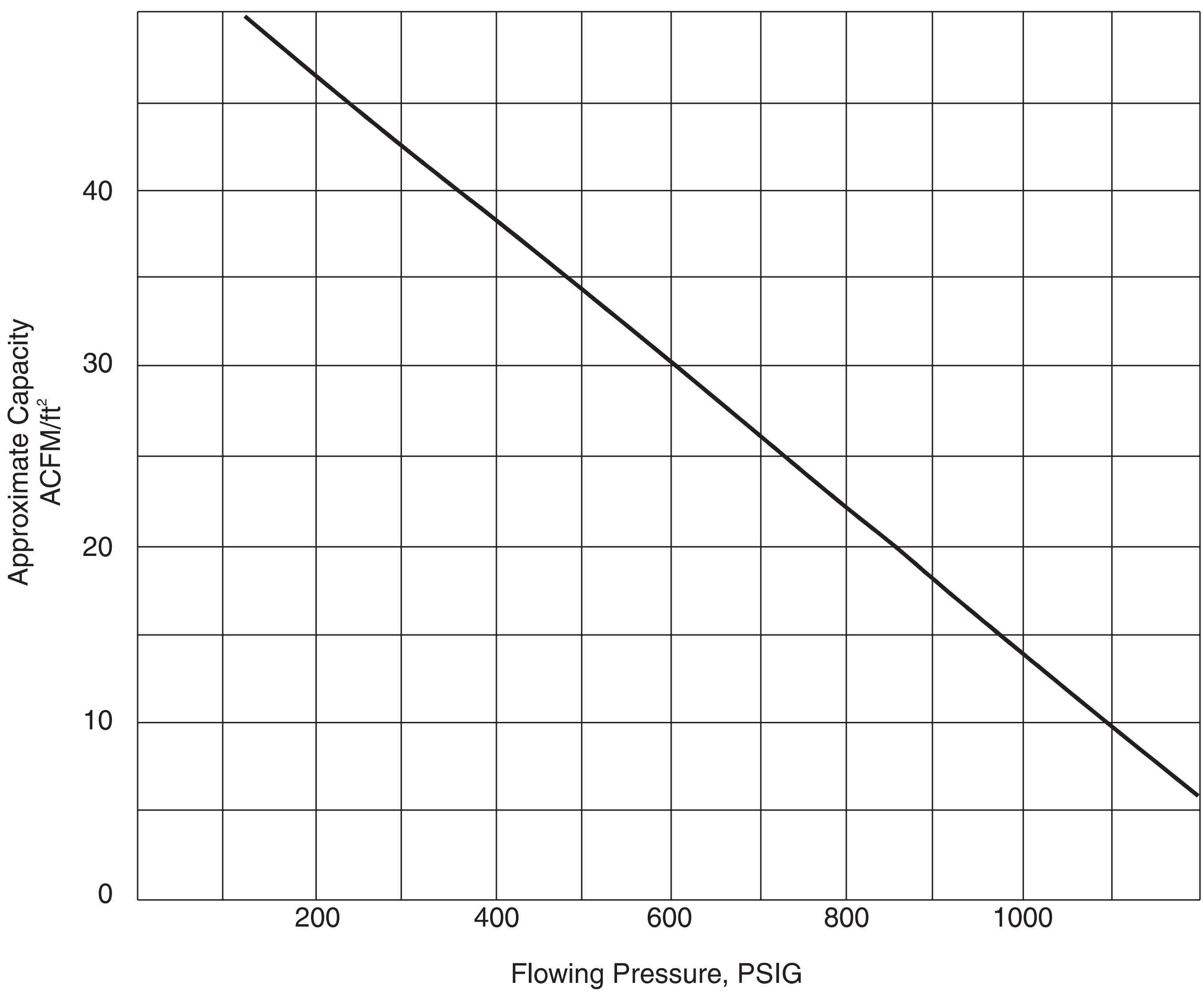
Since the droplet size of one liquid phase dispersed in another is usually unknown, it is simpler to size liquid-liquid separation based on retention time of the liquid within the separator vessel. For gravity separation of two liquid phases, a large retention or quiet settling section is required in the vessel. Good separation requires sufficient time to obtain an equilibrium condition between the two liquid phases at the temperature and pressure of separation. The liquid capacity of a separator or the settling volume required can be determined[10] from Eq 7-16 using the retention time give in Fig. 7-18.

$$U = \frac{W\,(t)}{1440} \qquad \textbf{Eq 7-16}$$

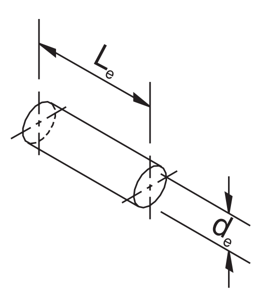
The following example shows how to size a liquid-liquid separator.

FIG. 7-16

Approximate Gas Filter Capacity



NOTES FOR FIG. 7-16:



Area of a Filter Element is: $\pi\ d_e\ L_e$
Filter Surface Area is:
(No. of Elements) $\pi\ d_e\ L_e$
where d_e, L_e are the Filter Element outside diameter and length respectively.

FIG. 7-17

Values of C* Used in Eq 7-14, 7-15

Emulsion Characteristic	Droplet Diameter, Microns	Constant[9] C*
Free liquids	200	1100
Loose emulsion	150	619
Moderate emulsion	100	275
Tight emulsion	60	99

FIG. 7-18

Typical Retention Times for Liquid/Liquid Separation

Type of Separation	Retention Time
Hydrocarbon/Water Separators[3]	
Above 35° API Hydrocarbon	3 to 5 min.
Below 35° API Hydrocarbon	
100°F and above	5 to 10 min.
80°F	10 to 20 min.
60°F	20 to 30 min.
Ethylene Glycol/Hydrocarbon Separators (Cold Separators)[11 14]	20 to 60 min.
Amine/Hydrocarbon Separators[11]	20 to 30 min.
Coalescers, Hydrocarbon/Water Separators[11]	
100°F and above	5 to 10 min.
80°F	10 to 20 min.
60°F	20 to 30 min.
Caustic/Propane	30 to 45 min.
Caustic/Heavy Gasoline	30 to 90 min.

Example 7-5 — Determine the size of a vertical separator to handle 600 bpd of 55° API condensate and 50 bpd of produced water. Assume the water particle size is 200 microns. Other operating conditions are as follows:

Operating temperature = 80°F
Operating pressure = 1000 psig
Water specific gravity = 1.01
Condensate viscosity = 0.55 cp @ 80°F
Condensate specific gravity for 55° API = 0.76

From Eq 7-14

$$W_{cl} = C^{*}\left(\frac{S_{hl} - S_{ll}}{\mu}\right)(0.785)\,(D_v)^2$$

From Fig. 7-17 for free liquids with water particle diameter = 200 microns, C* = 1100.

$$600 \text{ bbl/day} = 1100\frac{1.01 - 0.76}{(0.55)}(0.785)\,(D_v)^2$$

$$(D_v)^2 = \frac{600}{392.5} = 1.53 \text{ ft}^2$$

$$D_v = 1.24 \text{ ft}$$

Using a manufacturer's standard size vessel might result in specifying a 20" OD separator.

Using the alternate method of design based on retention time as shown in Eq 7-16 would give:

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

From Fig. 7-18, use 3 minutes retention time.

$$U = \frac{(650)\,(3)}{1440} = 1.35 \text{ bbl}$$

$$U = 1.35\,(42) = 56.7 \text{ gal}$$

Assuming a 20" OD, 1480 psig working pressure, a vessel would be made from 1.031" wall seamless pipe which holds 13.1 gal/ft. The small volume held in the bottom head can be discounted in this size vessel. The shell height required for the retention volume required would be:

$$\text{Shell height} = \frac{U}{\text{Vol/ft}} = \frac{56.7}{13.1} = 4.3 \text{ ft}$$

This would require a 20" OD x 10′ separator to give sufficient surge room above the liquid settling section for any vapor-liquid separation.

Another parameter that should be checked when separating amine or glycol from liquid hydrocarbons is the interface area between the two liquid layers. This area should be sized so the glycol or amine flow across the interface does not exceed approximately 2000 gallons per day per square foot.

The above example indicates that a relatively small separator would be required for liquid-liquid separation. It should be remembered that the separator must also be designed for the vapor capacity to be handled. In most cases of high vapor-liquid loadings that are encountered in gas processing equipment design, the vapor capacity required will dictate a much larger vessel than would be required for the liquid load only. The properly designed vessel has to be able to handle both the vapor and liquid loads. Therefore, one or the other will control the size of the vessel used.

PARTICULATE REMOVAL–FILTRATION

Filtration, in the strictest sense, applies only to the separation of solid particles from a fluid by passage through a porous medium. However, in the gas processing industry, filtration commonly refers to the removal of solids and liquids from a gas stream.

The most commonly used pressure filter in the gas processing industry is the cartridge filter. Cartridge filters are constructed of either a self-supporting filter medium or a filter medium attached to a support core. Depending on the application, a number of filter elements is fitted into a filter vessel. Flow is normally from the outside, through the filter element, and out through a common discharge. When pores in the filter medium become blocked, or as the filter cake is developed, the higher differential pressure across the elements indicates that the filter elements must be cleaned or replaced.

Cartridge filters are commonly used to remove solid contaminants from amines, glycols, and lube oils. Other uses include the filtration of solids and liquids from hydrocarbon vapors and the filtration of solids from air intakes of engines and turbine combustion chambers.

Two other types of pressure filters which also have applications in the gas processing industry include the edge and precoat filter. Edge filters consist of nested metallic discs, enclosed in a pressure cylinder, which are exposed to liquid flow. The spacing between the metal discs determines the solids retention. Some edge filters feature a self-cleaning design in which the discs rotate against stationary cleaning blades. Applications for edge filters include lube oil and diesel fuel filtration as well as treating solvent.

Precoat filters find use in the gas processing industry; however, they are complicated and require considerable attention. Most frequent use is in larger amine plants where frequent replacement of cartridge elements is considerably more expensive than the additional attention required by precoat filters.

The precoat filter consists of a coarse filter medium over which a coating has been deposited. In many applications, the coating is one of the various grades of diatomaceous earth which is mixed in a slurry and deposited on the filter medium. During operation additional coating material is often added continuously to the liquid feed. When the pressure drop across the filter reaches a specified maximum, the filter is taken off-line and back-washed to remove the spent coating and accumulated solids. Applications for precoat filters include water treatment for waterflood facilities as well as amine filtration to reduce foaming. Typical designs for amine plants use 1-2 gpm flow per square foot of filter surface area. Sizes range upward from 10-20 percent of full stream rates[7].

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