

## SECTION 7

# Separation Equipment

### 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 <sup>2</sup>                                                          | $Q_{l,max}$ = Maximum liquid volumetric flow rate, ft <sup>3</sup> /sec                                                         |
| $A_{mesh}$ = Mesh pad area, ft <sup>2</sup>                                          | $R$ = Gas constant, 10.73 (psia • ft <sup>3</sup> )/(°R • lbmole)                                                               |
| $A_p$ = Particle or droplet cross sectional area, ft <sup>2</sup>                    | $Re$ = Reynolds number, dimensionless                                                                                           |
| $C'$ = Drag coefficient of particle, dimensionless                                   | $Stk$ = Dimensionless Stokes Number: $\frac{g \cdot \rho_c \cdot V_c \cdot D_p^2}{18\mu_c \cdot D_c}$                           |
| $D$ = Vessel diameter, ft                                                            | $T$ = System temperature, °R                                                                                                    |
| $D_c$ = Characteristic diameter in the Stoke Number, St                              | $t$ = Retention time, min                                                                                                       |
| $D_H$ = Liquid hydraulic diameter, ft                                                | $V$ = Velocity, ft/sec                                                                                                          |
| $D_p$ = Droplet diameter, ft                                                         | $V_c$ = Velocity of continuous phase, ft/sec                                                                                    |
| $d_2$ = Nozzle diameter, ft                                                          | $V_h$ = Flow vapor velocity between gas-liquid interphase and the top of a horizontal separator, ft/sec                         |
| $d_{95}$ = Droplet size (micron) for 95% removal                                     | $V_l$ = Liquid velocity, ft/sec                                                                                                 |
| $g$ = Acceleration due to gravity, 32.2 ft/sec <sup>2</sup>                          | $V_r$ = Gas velocity relative to liquid, ft/sec                                                                                 |
| $GOR$ = Gas-oil ratio                                                                | $V_{r,max}$ = Maximum velocity of the gas relative to liquid to resist substantial re-entrainment                               |
| $H$ = Height, ft                                                                     | $V_t$ = Critical or terminal velocity necessary for particles of size $D_p$ to drop or settle out of a continuous phase, ft/sec |
| $H_{SET}$ = Settling height, ft                                                      | $W_g$ = Flow rate of gas, lb/hr                                                                                                 |
| $HILL$ = High interphase liquid level                                                | $W_l$ = Flow rate of liquid, lb/hr                                                                                              |
| $HHILL$ = High-high interphase liquid level                                          | $Z$ = Compressibility factor, dimensionless                                                                                     |
| $HLL$ = High liquid level                                                            |                                                                                                                                 |
| $HHLL$ = High-high liquid level                                                      | <b>Greek:</b>                                                                                                                   |
| $J$ = Gas velocity head, lb/(ft • sec <sup>2</sup> )                                 | $\beta$ = Ratio of the number of influent particles of a given size to the number of effluent particles of the same size        |
| $K$ = Souders-Brown Coefficient, ft/sec                                              | $\rho_c$ = Continuous phase density, lb/ft <sup>3</sup>                                                                         |
| $K_{CR}$ = Proportionality constant from Fig. 7-7 for use in Equation 7-6            | $\rho_g$ = Gas phase density, lb/ft <sup>3</sup>                                                                                |
| $L$ = Seam to seam length of vessel, ft                                              | $\rho_l$ = Liquid phase density, lb/ft <sup>3</sup>                                                                             |
| $L_{SET}$ = Effective gravity droplet settling length for a horizontal separator, ft | $\rho_{hl}$ = Heavy liquid phase density, lb/ft <sup>3</sup>                                                                    |
| $LILL$ = Low interphase liquid level                                                 | $\rho_{ll}$ = Light liquid phase density, lb/ft <sup>3</sup>                                                                    |
| $LLILL$ = Low-low interphase liquid level                                            | $\rho_m$ = Mixed fluid density, lb/ft <sup>3</sup>                                                                              |
| $LLL$ = Low liquid level                                                             | $\rho_p$ = Droplet or particle phase density, lb/ft <sup>3</sup>                                                                |
| $LLLL$ = Low-low liquid level                                                        | $\mu_c$ = Viscosity of continuous phase, cP                                                                                     |
| $M_p$ = Mass of droplet or particle, lb                                              | $\mu_g$ = Gas viscosity, cP                                                                                                     |
| $MW$ = Molecular weight, lb/lbmole                                                   | $\mu_{hl}$ = Heavy liquid phase viscosity, cP                                                                                   |
| $NILL$ = Normal interphase liquid level                                              | $\mu_{ll}$ = Light liquid phase viscosity, cP                                                                                   |
| $NLL$ = Normal liquid level                                                          | $\mu_l$ = Liquid viscosity, cP                                                                                                  |
| $N_{ref}$ = Reynolds film number                                                     | $\sigma$ = Liquid surface tension, dynes/cm                                                                                     |
| $N_\mu$ = Interfacial viscosity number                                               | $\Phi$ = Flow parameter                                                                                                         |
| $OD$ = Outside diameter, in                                                          |                                                                                                                                 |
| $P$ = System pressure, psia                                                          |                                                                                                                                 |
| $Q_A$ = Actual gas flow rate, ft <sup>3</sup> /sec                                   |                                                                                                                                 |
| $Q_l$ = Liquid volumetric flow rate, ft <sup>3</sup> /min                            |                                                                                                                                 |

## DEFINITIONS OF WORDS AND PHRASES USED IN SEPARATION EQUIPMENT

**Coalescing:** To come together to form a larger whole. The process or mechanism of bringing small droplets or aerosols and creating larger droplets that can more easily be removed by gravity. Also refers to the joining of liquid droplets dispersed in another immiscible liquid, as with water drops in oil.

**Gas coalescing filter:** A separator containing changeable elements that is capable of the removal of sub-micron aerosols and solids. This coalescing and filtering occurs as the gas flows from the inside of the filter/coalescing element to the outside of this element in the vertical filter-coalescer. Properly designed, this coalescing stage will remove solids and fine aerosols down to 0.3 micron and larger.

**Electrostatic coalescer:** A device used to remove dispersed water from oil by using a high voltage field to polarize and/or charge dispersed water droplets.

**Emulsion:** A stable dispersion of one immiscible liquid in another liquid.

**Entrainment:** Fluid in the form of a mist, fog, droplets, or bubbles carried along with the continuous phase.

**Filter:** A device used to separate solids from liquid or gas flow. Most filters utilize removable elements. Designs offering inline cleaning by back-flushing are also available.

**Filter separators:** A device to remove solids and entrained liquids from a gas stream. 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 drum:** A vessel which separates liquid, generated due to pressure reduction and/or increase in temperature of a liquid stream, from the gas phase or two phase fluid.

**Gas-oil ratio (GOR):** The ratio of gas to hydrocarbon at a defined condition, typically expressed as SCF/Bbl.

**Heater-treater:** A device used to process hydrocarbon, by warming and coalescence, in order to remove small quantities of residual water so as to meet transportation or product specifications.

**Line drop:** A boot or underground vessel, used on a pipeline, to provide a place for free liquids to separate and accumulate. It is used in pipelines with very high gas-to-liquid ratios to remove only free liquid from a gas stream. It will remove bulk liquid, but not necessarily all the liquid.

**Knock out drum:** Generic term used to describe vessels for gas-liquid separation. Separation can be either for high, or low, gas-to-liquid ratio streams.

**Liquid coalescer vessel:** A vessel, with internals designed for the separation of immiscible liquids.

**Liquid coalescer:** A vessel internal used for increasing the droplet size of immiscible liquids, so that they can be removed by gravity separation. Typical coalescing elements are stacked plates, vanes, wire or plastic mesh, or cartridge type elements.

**Liquid-liquid separators:** A vessel where two liquid phases are separated.

**Mist eliminator:** A fixed device used to enhance removal of smaller liquid droplets from a gas above which is not normally possible by gravity separation. Typical mist eliminator designs include knitted wire mesh, vane type, and cyclonic.

**Production separator:** A vessel typically used as the first separation device that the fluid encounters in the wellhead to processing plant production network (sometimes is called Wellhead Separator, when physically located at the well site).

**Retention time:** For gas-liquid separation, the average time a flowing fluid remains within the liquid section of a separator at the design feed rate. For three phase separation, the retention time can be the time the total fluid remains in the separation section at the design feed rate, or if defined as phase retention time, the time the phase remains in the separation section.

**Scrubber:** A category of separator used for streams with high gas-to-liquid ratios. Scrubbers are used as the primary separator in systems where small amounts of liquid are produced, to 'polish' an already-separated gas stream by removing residual contaminants more completely, or as a backup in case of an operational upset upstream.

**Separator:** A generic term for a device which separates gas-liquid, gas-liquid-liquid, gas-solids, liquid-solids or gas-liquid-solids.

**Slug catcher:** A particular separator design which is 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 at the terminus of the pipeline. A slug catcher may be a single large vessel or a manifolded system of pipes.

**Surge drum:** A vessel used to provide appropriate time for flow control and dampening during process variations and upsets. The capacity of the surge drum provides the ability to accept liquids from the upstream process, or provide liquids to downstream equipment without upsets.

**Surge time:** The time it takes to fill a specified fraction of a vessel, defined as the volume between a specified level range in a vessel divided by the design feed flow rate. 'Control' surge time is between the low liquid level alarm (LLL) and the high liquid level alarm (HLL). 'Total' surge time is between the lowest level (low-low liquid level, LLLL) and the highest level (high-high level, HHLL).

**Test separator:** A separator vessel used near the wellhead, which separates the phases for well test metering.

**Three phase separator:** A vessel used to separate gas and two liquids of different densities (e.g. gas, water, and oil) into three distinct streams.

# INTRODUCTION

## Scope

The Separation Chapter describes the types, function, application, design criteria, selection, and troubleshooting of separator vessels and devices, used from wellhead to treated product pipeline in the natural gas processing industry. Gas-liquid, liquid-liquid, gas-liquid-liquid, gas-solid, gas-solid-liquid, and liquid-solid devices are covered. The section addresses the primary separator at the well site for gas plants as well as common separation equipment in a gas treating facility. It does not provide substantial guidance on equipment used for water clean-up for re-injection or discharge, or for final treatment of liquid products. The scope does not include any discussion of the design of crude production separators and Gas-Oil Separation Process (GOSP) units for separation and treatment of crude oil, gas, and produced water. Note that some of the terms and design guidelines presented here may not be appropriate for crude oil service.

## Separation Devices Used in Gas Processing

A wide variety of separation vessel styles and devices are used in the natural gas processing industry. These include ver-

tical and horizontal vessels, two and three phase, many types of internals, as well as cyclonic devices, filter separators, gas coalescing filters, and gas and liquid filters. Fig. 7-2 shows a typical sour gas treating plant from wellhead to treated product pipeline. The common types of separators that are used within each process system are identified.

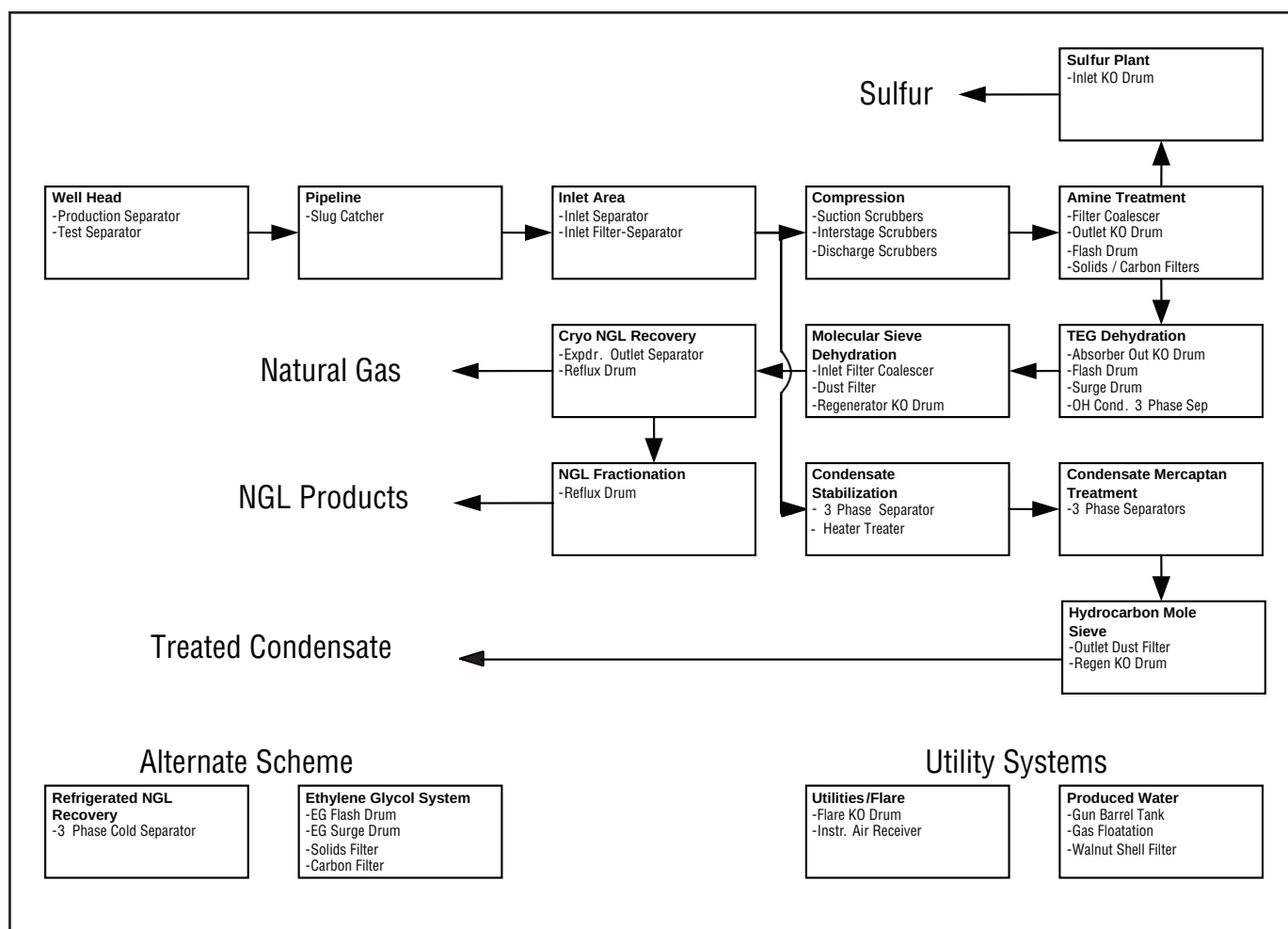
## PRINCIPLES OF SEPARATION

### Defining the Separator Feed

**Fluids to Be Separated** — Many types of fluids are separated in natural gas production and processing. While streams in downstream NGL recovery and processing may be well defined, the primary production stream can vary in composition, pressure, temperature, and impurities.

There are a number of terms used in the industry to characterize production and processing fluids. One such term is gas/oil ratio (GOR). The GOR is the ratio of the volume of gas that comes out of solution to the volume of oil, or condensate at either atmospheric pressure or at any specific process conditions. It is typically expressed as SCF/Bbl. In most production systems, produced water (production brackish water) will accompany the hydrocarbons. The amount of produced water is

FIG. 7-2  
Separators Used in Gas Processing Industry



typically expressed as Bbl/SCF gas. The hydrocarbon portion of production in the natural gas industry (both vapor and liquid phases) is typically characterized by component to  $C_6$  or  $C_8$ , and then as pseudo components, using MW and density, for heavier hydrocarbons. Water solubility, water entrainment, and trace components in the fluid should also be considered.

These characteristics, typically defined in the project or facility material balance, determine the gas, liquid, and solid phase flows and the properties for the fluids to be separated. The physical properties of the fluids are normally defined using equation of state models, and are supplemented by field physical property data where available. Special care should be used when utilizing simulator generated transport properties in the critical region of the phase envelope, or for cryogenic conditions.

## Field Composition and Flow Considerations

A separator must be designed to perform over the full range of flow rate and composition that may be present during the life of the facility. These might include changes in the  $CO_2$  or  $H_2S$  content, and how rich the gas is in natural gas liquids, or the production water cut. The vessel must also be designed considering changes in production flow due to reservoir depletion or gas break through. Adequate sizing and sufficient flexibility are required to handle anticipated conditions during the plant life. The possibility of flow variations due to slugs, flow surges, and compressor recycles should be considered. Frequently a design factor is added to the steady state flow rate to account for these variances in separator design. The magnitude of the factor depends on the location of the separator in the process. Also of concern is the presence of solids, either sand and/or iron sulfide in the production fluids.

## Dispersed Droplet Size Distribution

Because a primary driver in separation processes is acceleration (e.g., gravity), which is opposed by frictional forces (see Fig. 7-4), an understanding of the likely droplet size of the dispersed phase is important for proper selection and sizing of the separator and internals. The average droplet size and distribution is a function of the upstream processing and the effect of the inlet piping on the fluid to the separator. Typical droplet generation mechanisms for gas-liquid systems include: mechanical action like bubbling and frothing from tower trays, packing and distributors, surface condensation in a heat exchanger tube,

condensation due to cooling which does not occur on a surface, and shearing due to pressure drop through a valve or choke. Some typical liquid droplet sizes for liquid in a gas continuous phase are shown in Fig. 7-3. Also, as the liquid surface tension decreases (typical for light hydrocarbon systems at high pressure) the average droplet size formed by these processes will be smaller. The inlet piping flow characteristic is of interest since droplets can either coalesce into larger droplets, or be sheared by the gas phase in the piping. The velocity in the piping, elbows and bends, control valves, and hard "T"s all create shear that can result in fracturing larger droplets into smaller droplets. The higher the inlet velocity, higher the gas density, and the lower the liquid surface tension, the smaller the droplets. Use of inlet devices which shear the fluid (impact baffle plates/diverters) will also result in smaller inlet droplets.

Several correlations, which use the flow regime of the feed in the inlet pipe, and physical properties of the phases, are available to estimate this.<sup>1</sup> Oftentimes, however, past experience is used to set the target particle size expected, and in turn to be removed based on the specific unit operation in the plant, upstream processes, and the fluid to be separated.

For liquid-liquid separation, the effect of static mixers, mechanical agitators, centrifugal pumps, and high pressure drop control valves is also important in establishing the size distribution of droplets. Fine solids and certain chemicals (i.e., well treating chemicals) can stabilize fine droplets.

## Flow Regimes Upstream of a Separator

As a mixture of gas, hydrocarbon liquid, and water flows to a separator, the mixture can exhibit various behaviors, or flow patterns, depending on factors such as the relative flow rates of each phase, phase densities, elevation changes, and velocity. A number of empirical models have been developed for predicting flow pattern in a pipe. Possible flow patterns include mist flow, bubble flow, stratified flow, wavy flow, slugging flow, and annular flow. Stratified flow is an ideal flow regime entering a separator since the bulk phases are already segregated. Slugging and foaming flow are of particular concern to separator

FIG. 7-3

Typical Partial Size Distribution Ranges from Entrainment Caused by Various Mechanisms

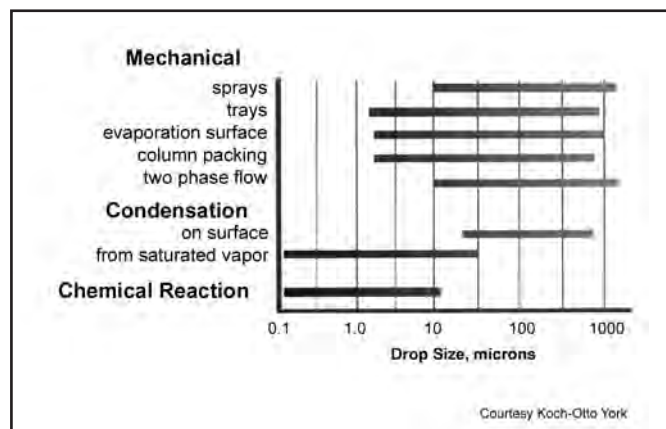
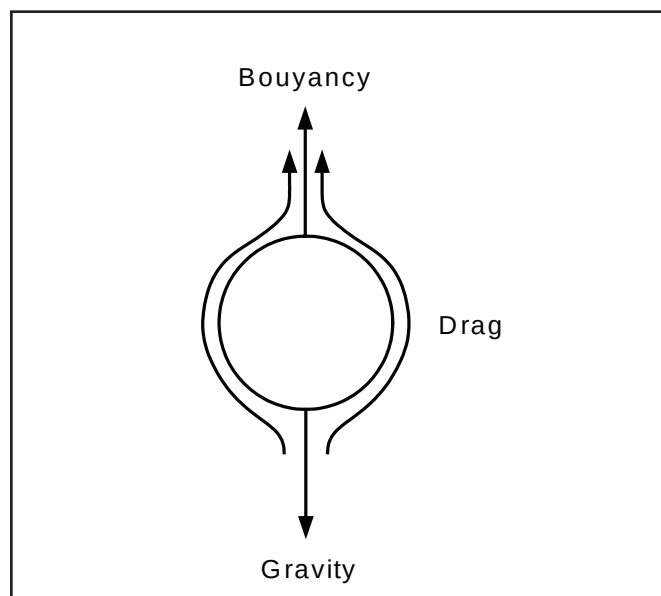


FIG. 7-4

Buoyant Force on a Droplet



design. Proper velocity and piping design upstream of the separator are critical for good separator performance (See “Two and Three-Phase Separator Design and Operating Principles- Inlet Section” in this Chapter for recommendations).

## Separation and Re-entrainment Mechanisms

The separation of two phases with different densities will occur by one of several mechanisms which are described in this section. The discussion is applicable to both gas-liquid and liquid-liquid separation.

**Gravity Settling Theory** — A summary of the equations defining the gravity settling mechanisms described below is presented in Fig. 7-7. The figure also includes general information regarding droplet sizes.

Dispersed droplets will settle out of a continuous phase if the gravitational force acting on the droplet is greater than sum of the drag force of the fluid flowing around the droplet and the buoyant force of the continuous phase (see Fig. 7-4). The terminal velocity of the droplet can be calculated directly from the balance of these forces, Equation 7-1.<sup>1</sup>

$$V_t = \sqrt{\frac{2 \cdot g \cdot M_p \cdot (\rho_p - \rho_c)}{\rho_p \cdot \rho_c \cdot A_p \cdot C'}} \quad \text{Eq 7-1}$$

The drag coefficient has been found to be a function of the shape of the particle and the Reynolds number of the flowing fluid. If the particle shape is considered to be a solid, rigid sphere, then the terminal velocity can be calculated using Equation 7-2:

$$V_t = \sqrt{\frac{4 \cdot g \cdot D_p \cdot (\rho_p - \rho_c)}{3 \cdot \rho_c \cdot C'}} \quad \text{Eq 7-2}$$

And the Reynolds number is defined in Equation 7-3.

$$Re = \frac{1,488 \cdot D_p \cdot V_t \cdot \rho_c}{\mu_c} \quad \text{Eq 7-3}$$

Fig. 7-5 shows the relationship between drag coefficient and particle Reynolds number for spherical particles.

In this form, a trial and error solution is required since both particle size ( $D_p$ ) and terminal velocity ( $V_t$ ) are involved. To eliminate trial and error iterations, the following technique eliminates the velocity term from the expression. The abscissa of Fig. 7-6 is given in Equation 7-4.

$$C' (Re)^2 = \frac{(0.95) \cdot (10^8) \cdot \rho_c \cdot D_p^3 \cdot (\rho_p - \rho_c)}{\mu_c^2} \quad \text{Eq 7-4}$$

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

As an alternative to using Equation 7-4 and Fig. 7-6 the following approach is commonly used.

The curve shown in Fig. 7-5 can be simplified into three sections from which curve-fit approximations of the  $C'$  vs.  $Re$  curve can be derived. When these expressions for  $C'$  vs.  $Re$  are substituted into Equations 7-2 and 7-3 (abscissa of Fig. 7-5), three settling laws are obtained as described below.

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

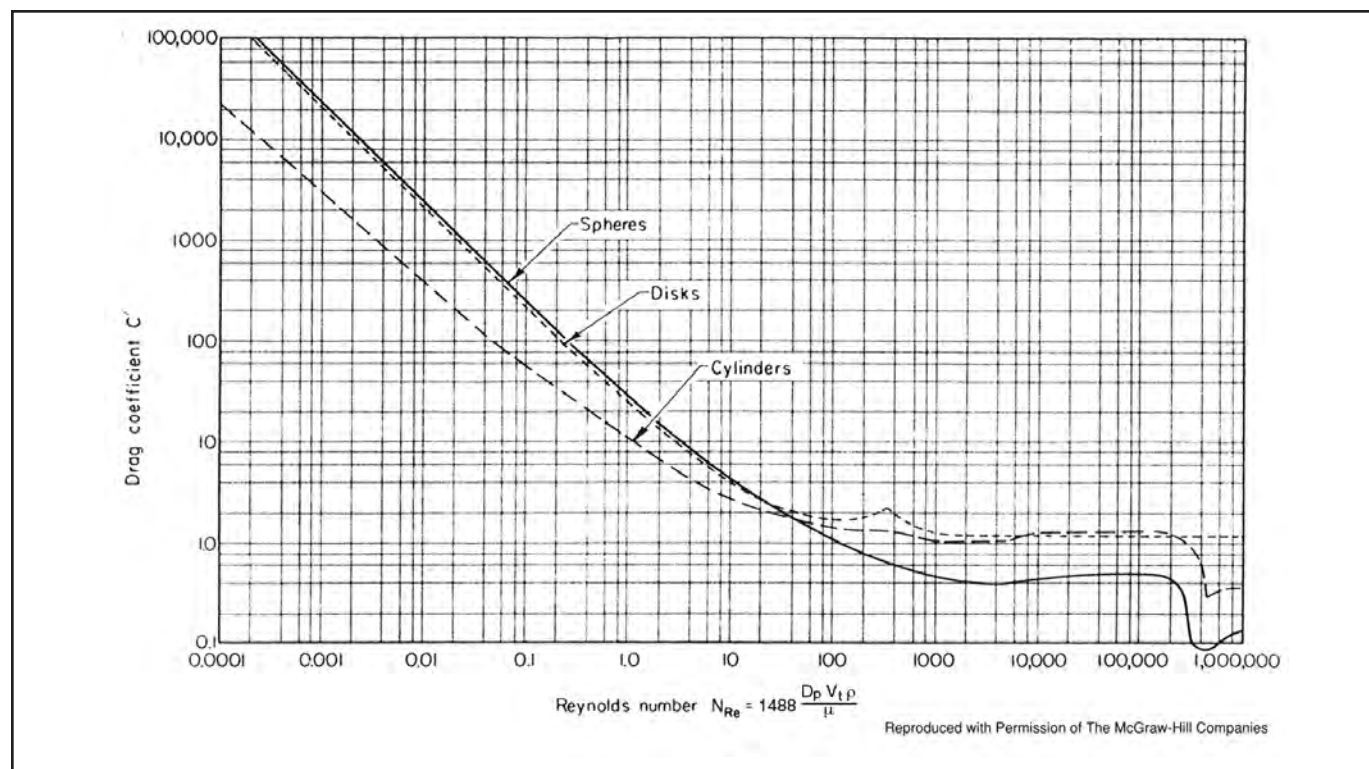
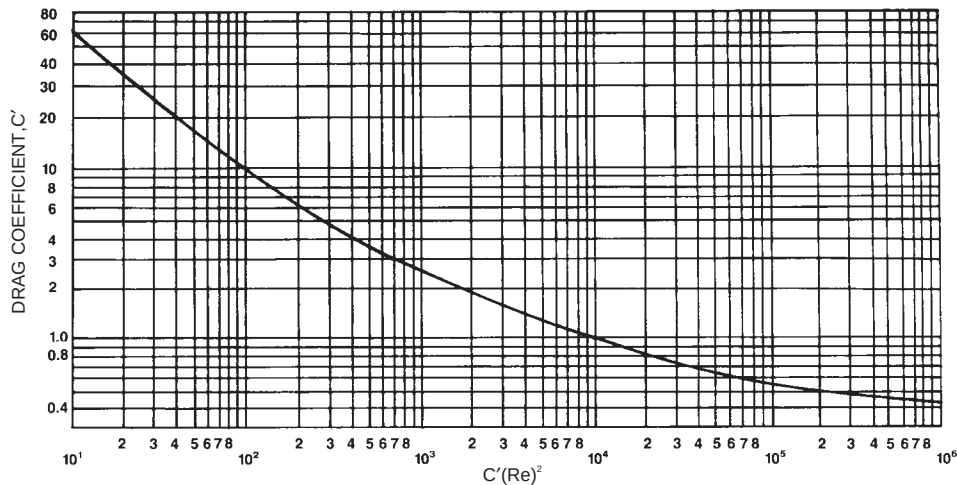


FIG. 7-6  
Drag Coefficient of Rigid Spheres



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

$$V_t = \frac{1,488 \cdot g \cdot D_p^2 \cdot (\rho_p - \rho_c)}{18 \mu_c} \quad \text{Eq 7-5}$$

To find the maximum droplet diameter that Equation 7-5 holds for, the droplet diameter corresponding to a Reynolds number of 2 is found using a value of 0.025 for  $K_{CR}$  in Equation 7-6.

$$D_p = K_{CR} \left[ \frac{\mu_c^2}{g \cdot \rho_c (\rho_p - \rho_c)} \right]^{1/3} \quad \text{Eq 7-6}$$

By inspection of the particle Reynolds number equation (Equation 7-3) it can be seen that Stokes' law is typically applicable for small droplet sizes and/or relatively high viscosity liquid phases.

**Gravity Settling Intermediate Law Region** — For Reynolds numbers between 2 and 500, the Intermediate Law applies, and the terminal settling velocity can be expressed as:

$$V_t = \frac{3.49 \cdot g^{0.71} \cdot D_p^{1.14} \cdot (\rho_p - \rho_c)^{0.71}}{\rho_c^{0.29} \cdot \mu_c^{0.43}} \quad \text{Eq 7-7}$$

The droplet diameter corresponding to a Reynolds number of 500 can be found using a value of 0.334 for  $K_{CR}$  in Equation 7-6.

The Intermediate Law is usually valid for many of the gas-liquid and settling applications encountered in the gas processing industry.

**Gravity Settling-Newton's Law Region** — Newton's Law is applicable for a Reynolds number range of approximately 500 to 200,000, and finds applicability mainly for separation of large droplets or particles from a gas phase, e.g. flare knock-out drum sizing. The limiting drag coefficient is approximately 0.44 at Reynolds numbers above about 500. Substituting  $C' =$

0.44 in Equation 7-2 produces the Newton's Law equation expressed as:

$$V_t = 1.74 \sqrt{\frac{g \cdot D_p \cdot (\rho_p - \rho_c)}{\rho_c}} \quad \text{Eq 7-8}$$

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  $K_{CR} = 18.13$ .

The latest edition of Perry's Chemical Engineers' Handbook indicates slightly different Reynolds number ranges for the applicable regimes, and a different drag coefficient correlation for the intermediate regime. The differences, however, are within the accuracy of the equations.

Fig. 7-8 shows the impact of hydrocarbon density and viscosity on the Stokes' Law terminal settling velocity of a water droplet in a hydrocarbon continuous phase.

**Example 7-1** — Calculate the terminal velocity using the drag coefficient and Stokes' Law terminal settling velocity in a vertical gas-liquid separator for a 150 micron particle for a fluid with the physical properties listed below.

Physical Properties

$$\rho_g = 2.07 \text{ lb/ft}^3, \mu_g = 0.012 \text{ cP}, \rho_l = 31.2 \text{ lb/ft}^3$$

$$\text{Particle Diameter, } D_p = (150 \cdot 0.00003937)/(12) = 0.000492 \text{ ft}$$

From Equation 7-4,

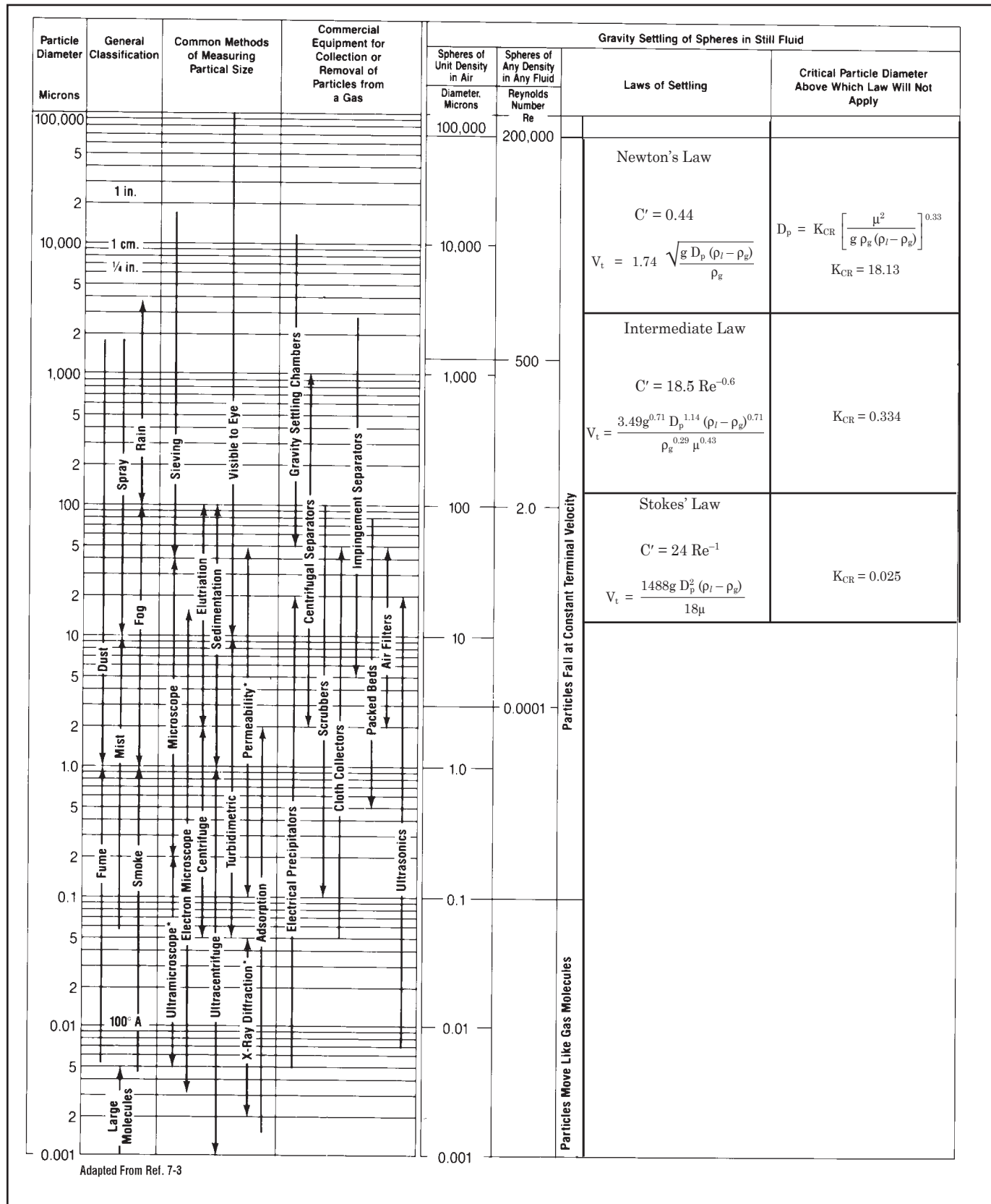
$$C'(\text{Re})^2 = ((0.95) \cdot (10)^8 \cdot (2.07) \cdot (0.000492)^3) / (31.2 - 2.07) / (0.012)^2 = 4738$$

From Fig. 7-5, Drag coefficient,  $C' = 1.4$

Terminal Velocity,

$$V_t = \left[ \frac{(4 \cdot 32.2 \cdot 0.000492 \cdot (31.2 - 2.07))}{(3 \cdot 2.07 \cdot 1.4)} \right]^{0.5} = 0.46 \text{ ft/sec}$$

**FIG. 7-7**  
**Gravity Settling Laws and Particle Characteristics**



## Separation by Impingement

Frequently in the natural gas industry, gravity settling alone is not sufficient to achieve the required separation results and internals are required to assist in the separation. The most widely used type of device for droplet collection is an impingement type device. These devices use baffles, wall surface, vanes, wire, or fiber to achieve separation via inertial impaction, direct interception, or diffusion.

**Inertial Impaction** — Inertial impaction occurs when, because of their mass, droplets will have sufficient momentum to break free of the gas streamline and continue to move in a straight line until they impinge on a target. This is the primary capture mechanism for mesh, vane, and cyclone mist eliminators. The capture efficiency of most mist elimination devices has been found to be related to the Stokes Number,  $Stk$ , as described in the Nomenclature for this Chapter.  $D_c$  is a characteristic diameter for the particular device (i.e.  $D_c$  is the wire diameter for a mesh mist eliminator, and  $D_c$  is the tube diameter for cyclones).<sup>2, 4</sup>

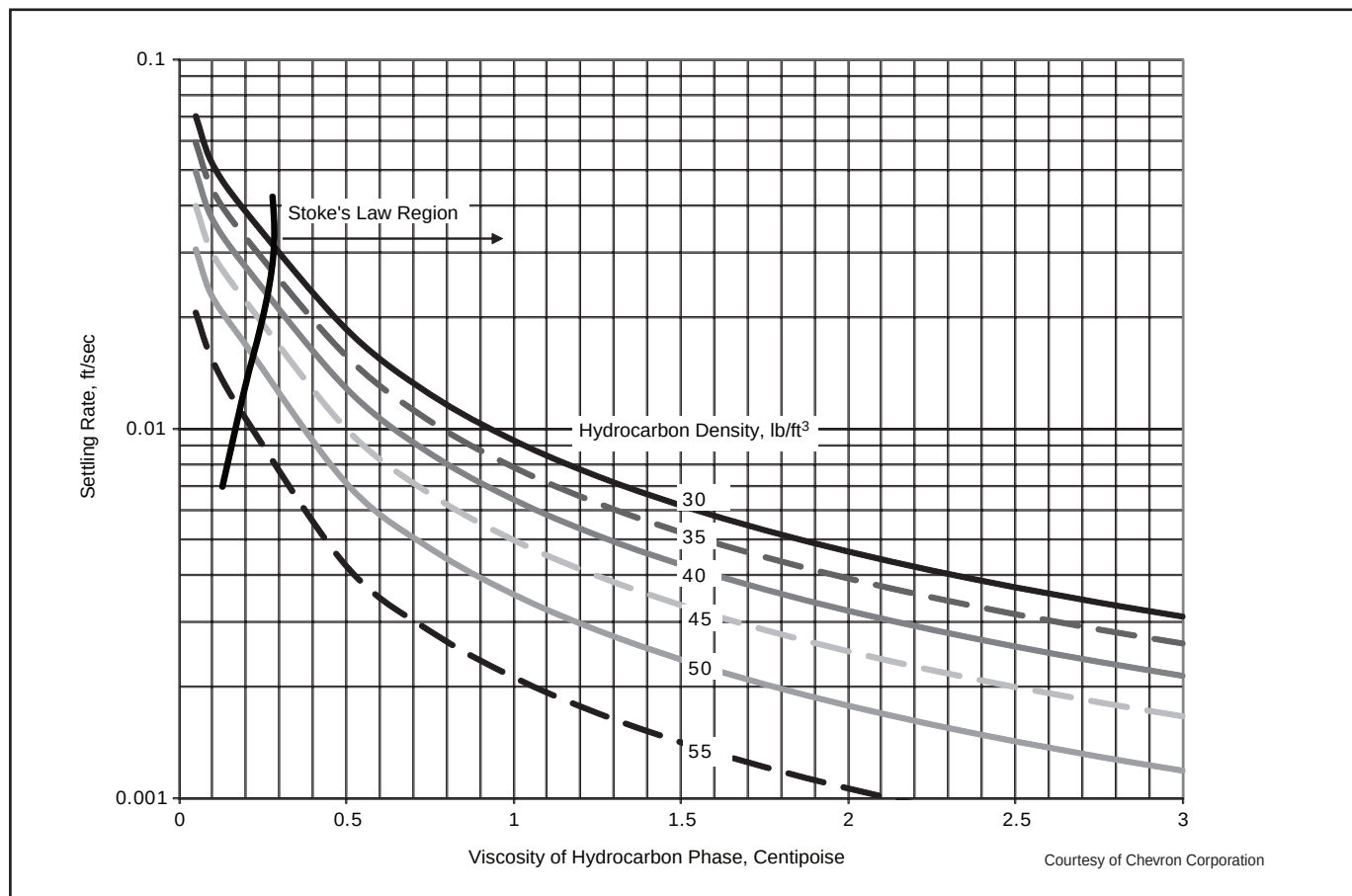
**Direct Interception** — Direct interception occurs when particles are small enough to remain on the gas streamline, and are collected if the droplets pass close enough to the target such that it touches the target. It is a secondary capture mechanism for mesh mist eliminators.

**Diffusion** — Very small particles (typically less than 1 micron) exhibit random Brownian motion caused by collision with gas molecules. This random motion can cause the particles to strike a target. Diffusion is not a primary mechanism for most separation devices used in the gas processing industry.

**Centrifugal Force** — Separation of particles can also be enhanced by the imposition of radial or centrifugal force. The typical flow pattern involves the gas spiraling along the wall of a device. The flow patterns are such that radial velocities are directed toward the wall causing the droplets to impinge on the wall and be collected.

**Coalescing, Natural and Assisted** — Natural coalescing occurs when small droplets join together to form fewer, larger droplets. This process will typically occur very slowly for dispersed droplets in a continuous phase due to limited collisions between droplets. Coalescing can be accelerated by flowing the mixture through media with high specific surface area. In gas-liquid separation, liquid droplets coalesce on the demisting device and drain by gravity to the bulk liquid. In liquid-liquid separation, coalescence is used in the same way to produce larger droplets that can more easily settle by gravity. This is done using parallel plate (enhanced gravity separation) or by contact with a target media such as wire mesh.

FIG. 7-8  
Settling Rate of 100-micron Diameter Water  
Droplet in Hydrocarbons



## Gas-Liquid Surface Re-entrainment

When gas flows across a liquid surface, it may re-entrain liquid from the gas-liquid interface to the gas phase. As the gas velocity increases, waves form and build at the liquid surface, releasing liquid droplets into the flowing gas stream. The extent of re-entrainment is a function of the gas velocity, density, and transport properties, including liquid surface tension and gas and liquid viscosity. Reducing surface re-entrainment to a minimum is typically a key design goal for horizontal gas-liquid separators. Criteria for the inception of re-entrainment from a gas-liquid interface surface were developed by Ishii and Grolmes<sup>5,24</sup>, and others.

The Ishii-Grolmes criteria can be used to estimate the maximum allowable gas velocity at incipient entrainment in a horizontal separator vapor zone. As shown in Fig 7-9, the criteria is divided into five regimes, based on the Reynold's film number,  $N_{ref}$ , and interfacial viscosity number,  $N_\mu$ , Equations 7-9 and 7-10, respectively. Re-entrainment is more likely at higher  $N_{ref}$  values. Consequently, gas velocities must be kept lower to prevent re-entrainment. For each design case, Fig. 7-9 should be referenced to determine the controlling equation.

$$N_{ref} = \frac{1488 \rho_l V_l D_H}{\mu_l} \quad \text{Eq 7-9}$$

and

$$N_\mu = \left[ \frac{0.066 \mu_l}{\rho_L \sigma \left( \frac{\sigma}{g(\rho_l - \rho_g)} \right)^{0.5}} \right]^{0.5} \quad \text{Eq 7-10}$$

**Re-entrainment from Collection Devices** — Re-entrainment from a collection device is the mechanism where the gas moving through the device causes a previously collected fluid to be removed off the element and carried away by the bulk stream. Surface re-entrainment is a function of the gas flow rate, liquid loading of the device, as well as the physical and transport properties of the gas and liquid (including the gas and liquid viscosity and liquid surface tension). Re-entrainment is always the limiting factor in the design of collection devices.<sup>6</sup>

**Degassing of Liquids** — The rise rate of a bubble of a given size can be calculated using gravity settling theory, according to Equation 7-2. For most applications, the separation vessel is sized so that there is enough retention time for the entrained gas to be released from the liquid. This is most critical where vapor carry-under is undesirable for contamination reasons, for proper pump performance, or in applications such as physical solvent treating systems where carry-under can affect the process specifications. For most applications, if bubbles larger than 200  $\mu\text{m}$  are able to escape, then carry-under will be negligible. The rise rate for a 200  $\mu\text{m}$  bubble typically will be

in the Stokes' Law Settling Region and can be estimated using Equation 7-5. For light fluids frequently encountered in the gas processing industry, a retention time of 1-2 minutes is generally adequate for degassing. For good degassing of a liquid, retention time must increase with increasing gas density and liquid viscosity. See "Design of Liquid Accumulators" in this Chapter.

## Gas-Liquid Separation Fundamentals

Liquid separation from the gas phase can be accomplished by any combination of the separation mechanisms previously described.

**Souders-Brown Equation for Gravity Settling** — Gravity settling of a liquid droplet in a gas can be described by Equation 7-2. This equation can be simplified to describe the liquid spherical droplet terminal velocity as a function of the droplet diameter, and the drag coefficient. The simplified form of the terminal velocity equation is called the Souders-Brown Equation<sup>7</sup>. The equation is valid for vertical gas flow, where the drag due to upward gas flow and the downward gravity force are in balance. The equation is also frequently used to determine the downward vertical terminal velocity of droplets in horizontal fluid flow, even though this relationship is not as rigorous, especially at higher fluid velocities.

The Souders-Brown equation<sup>7</sup> is used in a number of ways to design equipment for gravity settling in the oil and gas industry. A target droplet capture diameter can be specified for a gravity settling application, and then using the settling laws, and fluid properties, a drag coefficient,  $K$ , and terminal droplet velocity can be calculated, or determined by empirical testing. The  $K$ -factor is also a function of separator geometry, including settling space both upstream and downstream of the mist eliminator.

$$V_t = K \cdot \sqrt{\frac{(\rho_l - \rho_g)}{\rho_g}} \quad \text{Eq 7-11}$$

Where,

$$K = \sqrt{\frac{4gD_p}{3C'}} \quad \text{Eq 7-12}$$

**Gravity Settling in Gas-Liquid Separation** — In vessels with no internals, gravity settling is the only mechanism of separation. Thus, terminal velocity of the minimum particle size desired for separation is critical. For vertical vessels, a liquid droplet will settle out of the gas phase when the vertical gas velocity is less than the droplet's terminal velocity. The terminal droplet velocity can be obtained by using the appropriate settling law expression, or an industry experience  $K$  value. The  $K$  value can be calculated by assuming a minimum droplet size that must be removed and equating Equation 7-11 and Equation 7-12. The target droplet diameter, or  $K$  value, is selected to prevent excessive entrainment based on experience. In either case a target droplet size of about 250 to 500 microns is typically used for many gas-liquid gravity separator designs. This approach has been found to be adequate to prevent substantial liquid carryover for most applications. The maximum allowable  $K$  value used for design, for light hydrocarbon applications, is frequently reduced further at elevated pressures from that calculated by Equation 7-11. This is intended to account for the fact that as the pressure increases, the surface tension for light hydrocarbons decreases, as well as the high gas density, resulting in a higher likelihood of a smaller mean droplet size entering the separator.

For a vertical separator the required cross-sectional area

FIG. 7-9  
Ishii-Grolmes Criteria

| Eq | $N_{ref}$               | $N_\mu$       | $V_{r, max}$                                                                          |
|----|-------------------------|---------------|---------------------------------------------------------------------------------------|
| A  | <160                    | —             | $4.92 (\sigma/\mu_l) (\rho_l/\rho_g)^{0.5} \cdot N_{ref}^{-0.5}$                      |
| B  | $160 < N_{ref} < 1,635$ | $\leq 0.0667$ | $38.64 (\sigma/\mu_l) (\rho_l/\rho_g)^{0.5} \cdot N_\mu^{0.8} \cdot N_{ref}^{-0.333}$ |
| C  | $160 < N_{ref} < 1,635$ | $> 0.0667$    | $4.43 (\sigma/\mu_l) (\rho_l/\rho_g)^{0.5} \cdot N_{ref}^{-0.333}$                    |
| D  | $> 1,635$               | $\leq 0.0667$ | $3.28 (\sigma/\mu_l) (\rho_l/\rho_g)^{0.5} \cdot N_\mu^{0.8}$                         |
| E  | $> 1,635$               | $> 0.0667$    | $0.376 (\sigma/\mu_l) (\rho_l/\rho_g)^{0.5}$                                          |

to prevent carryover of a given droplet diameter is defined in Equation 7-13.

$$A = \frac{Q_A}{V_t} \quad \text{Eq 7-13}$$

In theory, for horizontal vessels, the terminal liquid droplet velocity can be used to define the horizontal length required to settle a droplet out of the gas phase before it reaches the gas outlet, for a given gas velocity and depth to the surface. Therefore the theoretical maximum horizontal vapor velocity can be written in terms of the terminal velocity as follows:

$$V_h (\text{max}) = \frac{L_{\text{SET}}}{H_{\text{SET}}} \cdot V_t \quad \text{Eq 7-14}$$

Equation 7-14 is predicated on the settling force balance applying strictly to horizontal flow, an ideal vapor profile, no eddies, and neglects end affects. In practice, a safety factor is required in the design to account for these affects. For many applications, the above approach, if applied for a typical vessel L/D ratio of 3:1 or greater, would result in a effective axial flow K factors ( $L/H \cdot K$ ) greater than 1.0. In practice, the effective K used has been limited by either calculation of the incipient re-entrainment velocity, an empirical approach, or both.<sup>5</sup> See “Two-Phase and Three Phase Separator Design and Operating Principles Gravity Separation Section” in this Chapter.

## Mist Eliminators for Gas Liquid Separations

**Mechanism of Mist Carryover for Gas-Liquid Mist Eliminator Devices** — Mist eliminators are commonly used in gas-liquid separation to aid gravity separation in the removal of liquid so that more efficient, smaller separators may be used. To be effective, a mist eliminator must accomplish two basic functions. First, it must have a means to capture liquid. Second, it must be able to drain the captured liquid without allowing re-entrainment into the gas stream. There are two mechanisms of liquid carryover from a mist eliminator. In the first mechanism, carryover is due to droplets of mist which are simply not captured by the device. The droplets might be too small to be captured or velocities are too low, causing low efficiency for impaction-type mist extractors. The second is re-entrainment of liquid after it has already been captured in the mist eliminator.

The majority of separator failures are caused by re-entrainment. This is the mechanism that occurs as the gas throughput is increased beyond the tolerable limit. Gas moving through the mist extractor exerts a drag force on the liquid film of the mist eliminator, causing it to be pulled toward the trailing edge of the device. If the drag is excessive, the liquid will be torn off the element and carried away by the gas stream. As flow rate increases, the contact efficiency of most mist eliminators im-

proves. Therefore, increasing gas flow yields improved droplet capture, but also increases re-entrainment which results in liquid carryover and limits separation capacity.

**Souders Brown Equation Applied To Mist Eliminators** — The Souders-Brown Equation (Equation 7-11) is frequently used to correlate the maximum capacity for mesh, vane, and cyclonic mist eliminators in a similar manner to flooding criteria for towers. While commonly used, this approach can be overly simplistic, since other mechanisms can influence the ultimate capacity of a device. The device supplier literature K coefficient published in catalogues is typically obtained from empirical test data for air-water systems at low pressure, and in theory, is valid for favorable operating conditions with different fluids. For other systems, gas and liquid viscosity, liquid surface tension, liquid loading, and foaming tendency are also factors in setting the device gas load capacity. The required mist extractor area is obtained from the design K, or other design limits, and is typically selected to provide a certain degree of margin before liquid entrainment/carryover becomes excessive.

**Mesh Mist Eliminators** — Mesh mist eliminators or pads are made by knitting wire, metal, or plastic into tightly packed layers, which are then crimped and stacked to achieve the required pad thickness. Mesh pads remove liquid droplets by impingement of droplets onto the wires, followed by coalescence into droplets large enough to disengage from the bottom of the pad and drop through the rising gas flow into the liquid holding part of the separator. The prominent mechanism for droplet capture is inertial impaction. The capture efficiency for a conventional mesh mist eliminator, at a given droplet size, is a function of the wire or fiber total thickness, mesh density, and wire diameter, as well as properties of the fluids to be separated. Smaller wire/fiber size and thicker mesh are more efficient. Droplet capture efficiency is related to the Stokes Number (see Nomenclature Section), specific surface area of the mist eliminator, number of layers, and other factors. For a typical service condition, and mesh style and thickness, a droplet size with a capture efficiency of 95% ( $d_{95}$ ) can be determined. Droplets larger than this will be captured almost completely. Smaller droplets will have a lesser capture efficiency. Given an inlet droplet distribution, a total capture efficiency can be predicted.<sup>2,9</sup>

The most common style of mesh mist eliminator used in gas processing is a 4 in. to 6 in. thick crimped wire mesh pad with 9 to 12 lb/ft<sup>3</sup> bulk density. High droplet removal efficiency for droplets 10 microns and larger is common for the above design. Other designs include fiber mesh, mixed wire and fiber mesh, multiple mesh density layers, and special drainage channels. The goals are either to increase removal efficiency at

FIG. 7-10

Wire Mesh Mist Eliminator

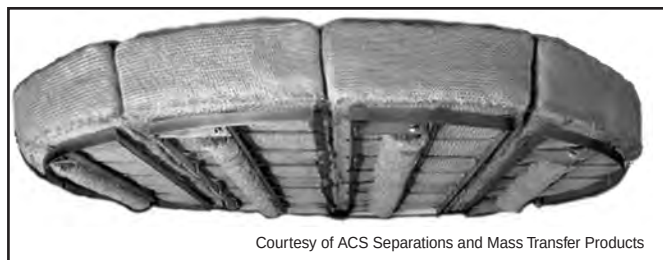
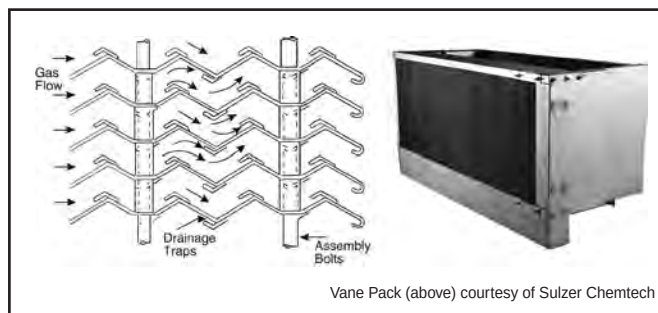


FIG. 7-11

Cross-Section of Vane Element Mist Extractor and Typical Vane Pack



lower droplet diameters, promote better drainage and in turn less carryover, increase throughput for a given mist eliminator area, reduce fouling, or a combination of the above. Manufacturers should be contacted for specific designs. Mesh pads are not recommended for dirty or fouling service as they tend to plug easily and can dislodge at high differential pressure.<sup>10</sup> A typical mesh mist eliminator is shown in Fig. 7-10.

Proper drainage of the mesh mist eliminator is essential to the operation of the unit. As the gas velocity increases at a given inlet liquid loading, the liquid continues to drain until a limiting load point is reached, at which point substantial liquid will carry over with the gas flow. Most mesh mist eliminator designs are based on the load point velocity. The load point will depend on the mist eliminator orientation, since the drainage mechanism is different as the pad orientation changes.

The maximum design Souders-Brown K value is frequently used to quantify the gas capacity of a wire mesh pad and depends upon factors such as mesh type, mesh material, wire packing density, and specific surface area, as well as the fluid properties. Mist eliminator suppliers typically will provide in their catalogues a design K value for their products suitable for design for many applications. At other conditions, the design K value may be lower, due to the liquid load to the device, liquid viscosity, foaming tendency, liquid surface tension, gas mal-distribution, and flow surges.<sup>4, 9</sup>

Separator configurations, sizing considerations, and typical K factors for mesh pad equipped separators are discussed further in the “Two-Phase and Three Phase Separator Design and Operating Principles — Gas Polishing Section” of this Chapter.

**Vane Mist Eliminators** — Vane or chevron-type mist eliminators (vane-pack) use relatively closely spaced blades arranged to provide sinusoidal or zig-zag gas flow paths. The changes in gas flow direction combined with the inertia of the entrained liquid droplets cause impingement of the droplets onto the plate surface, followed by coalescence and drainage of the liquid to the liquid collection section of the separator. Vane packs may be installed in either horizontal or vertical orientations. Various vane styles are available, including those with and without pockets (both single and double pockets) to promote liquid drainage. Vanes with pockets, allow a higher gas throughput per flow area due to enhanced drainage, but are not typi-

cally used in highly fouling service. Fig. 7-11 shows a horizontal, pocketed vane-type mist eliminator. Vane capacity is reduced for vertical up flow applications relative to horizontal flow.

Key performance parameters for vanes are droplet removal efficiency and gas handling capacity. Capture efficiency for a given droplet size depends on the vane design, gas velocity, gas viscosity and other parameters. Simple vanes with no pockets are typically capable of capturing 40 microns droplets, pocketed vanes are capable of 20 microns, and highly complex vanes of 10-20 microns at favorable operating conditions. Maximum vane capacity is set to limit re-entrainment. The Souder-Brown equation (Equation 7-11) and the load/sizing K factor are frequently used for describing the capacity of vane-type mist eliminators. Manufacturers provide typical K factors for the various styles. The capacity for a particular vane service may be limited due to the liquid load to the device, liquid viscosity, foaming tendency, liquid surface tension, gas mal-distribution, and flow surges. These factors are not necessarily directly related to the Souders-Brown K value. Manufacturer guidance is necessary for a design.<sup>11, 26</sup>

Testing has shown that for mesh type mist eliminators the low pressure air-water droplet removal efficiency experimental results correlate reasonably well with higher pressure gas-hydrocarbon liquid systems. Vane packs on the other hand show a drop-off in removal efficiency as pressure increases. This is primarily due to the decreased allowable design gas velocity caused by the increased gas density. As gas velocity decreases, droplet inertia decreases, and the droplets tend to follow the gas streamlines through the vane passages more easily. As a result, droplets are able to exit the vane pack without being captured. Mesh pads also rely on velocity/droplet inertia to remove liquid droplets via impingement, but they are less susceptible to efficiency reduction than vane packs because mesh pads have far more collection “targets”, i.e. wire/fiber filaments.

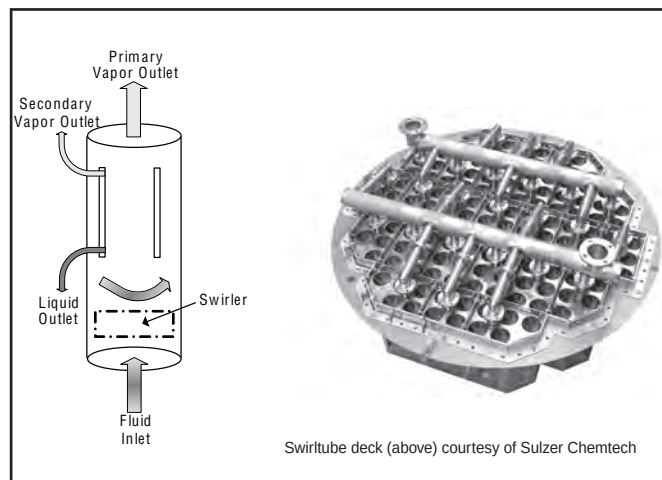
Turndown is generally more of a concern with vane-packs than wire mesh, with droplet removal efficiency decreasing measurably as velocity decreases from design. Vane packs are more tolerant to dirt and fouling than mesh due to the large passage size.

Typical vane separator vessel arrangements are shown in the Types of Common Gas-Liquid Separators Section of this

**FIG. 7-12a**  
**Reverse Flow Cyclone**



**FIG. 7-12b**  
**Axial Flow Cyclone Schematic and Swirltube Deck**



Chapter. For comparison purposes, typical K values for vane separators are shown in Fig. 7-37.

**Cyclonic Mist Eliminators** — Cyclonic mist eliminators use centrifugal force to separate liquid droplets and solids from the gas phase based on density difference. Very high G forces (multiples of gravity) can be achieved, which allows for efficient removal of small droplets. The main advantage of cyclonic mist eliminators is that they provide good removal efficiency at high operating pressure, and at high gas capacity. This typically allows for the smallest possible vessel diameter for a given gas flow. In order to create the high G-forces required, cyclonic separators generally have significantly higher pressure drops than other separation mechanisms. They also have less turn down capability because the G-forces are reduced at lower gas velocities.<sup>4</sup>

There are many types of centrifugal devices used in the industry to separate entrained liquids and solids, from a gas stream. The two most common configurations employed are reverse flow cyclones and axial-flow cyclones. In conventional reverse flow cyclones, each cyclone element consists of a tangential inlet, a cone shaped bottom section, and an upper center gas outlet. The gas swirls downward through the annulus between the inner and outer walls. It then flows, still spinning, into the inner tube and exits out the top. In the axial flow cyclones, the wet gas flows up through a swirl element which induces a spinning flow. The high tangential velocity throws the liquid droplets to the walls of the cylindrical tube, where they form a thin film. The liquid film exits through slots in the cyclone walls, along with a small amount of gas, and then drains to the bottom of the unit. Several techniques can be used to recover liquids from the purge gas.<sup>27</sup>

In order to achieve efficient operation in the most compact space, and for the best recovery for the energy expended, cyclone systems for gas-liquid separation are assembled in multi-cyclone “bundles”. The entire bundle is considered the cyclone separator device. Examples of a reverse flow cyclone tube, and an axial cyclone tube with swirltube deck are shown in Figs. 7-12a and 7-12b, respectively.

In addition to the above styles, the principle of cyclonic force is used in a large number of traditional and cutting edge technology for separation of gas-liquid and gas-liquid-solids in the industry.

## LIQUID-LIQUID SEPARATION FUNDAMENTALS

Separation between two liquid phases is not usually limited by re-entrainment, but rather by the mixture’s inability to separate due to the characteristics of the two liquids or the size of the separator. Two sizing characteristics are commonly used to calculate liquid separator sizing: droplet settling velocity and retention time.

### Gravity Settling in Liquid-Liquid Separation

Droplet settling due to gravity can be used to size liquid separators. Since these separators are most often designed to be in laminar flow to provide reasonable quality separation, Stokes’ Law, Equation 7-5, can be typically applied with appropriate safety factors. For horizontal vessels, a dispersed liquid droplet will settle out of the continuous phase when the droplet has sufficient time to reach and be absorbed into the liquid-liquid interface before it reaches the continuous phase draw-off connection.

For vertical vessels, a dispersed liquid droplet will settle out when the vertical continuous phase velocity is less than the terminal velocity of the droplet. Stokes’ law is based on free fall of liquid droplets through a stagnant continuous phase, when the dispersed phase is dilute. Safety factors must be applied when using Stokes’ Law to account for the fact that the flow regime in the separator frequently can be turbulent with eddies and currents and the droplets are not necessarily spherical. In addition, the axial velocity must be limited to minimize turbulence in the separator. Other design factors and/or sizing methods are required where the dispersed concentration is high enough to hinder settling, or where a dispersion layer can be present.<sup>12</sup> See “Gas-Liquid-Liquid Separator Design” in this Chapter.

In a three-phase separator, liquid-liquid (oil-water) separation occurs concurrently with the degassing function, but due to the relatively small density difference of oil and water it progresses more slowly. Since water removal from hydrocarbon liquid is slower than gas removal, a three-phase separator typically has a longer liquid retention time — 3-5 minutes for light oils, longer for heavier liquids. This typically means a larger separator is required for three phase separation than for two-phase separation.

Oil-water separation requires both separation of water from the oil phase (de-watering), and of oil from the water phase (de-oiling). Generally, water de-oiling is much easier than oil de-watering, for heavier oils (crude oil), because of the lower viscosity of the continuous water phase. This is fortunate because the requirements are typically more severe for water quality due to disposal considerations. This is the case even though further treatment is often required of both oil and water. Typical quality specifications for effluent oil are usually stated in percent, while for water specifications are normally stated in parts per million.

Small droplet dispersions of water-in-oil, or oil-in-water may be stabilized by natural or added surfactants, resulting in an emulsion which may not be separable in a gravity separator. A chemical additive upstream of the separator may be needed to de-stabilize such emulsions.

### Liquid Residence Time Approach to Design

Liquid residence time is defined as the length of time a fluid remains within the settling compartment of the separator. Longer retention times generally result in a more thorough separation. Actual retention time in a separator is shorter than the idealized or theoretical retention time because of non-uniform flow profiles such as channeling and recirculation. Actual retention time may be made to approach the idealized retention time by achieving a more uniform velocity profile. Perforated distribution baffles are often used to aid liquid distribution. Designing for similar superficial horizontal velocities in both oil and water phases also improves the velocity profile by reducing shear at the liquid-liquid interface.

Selection of residence time is generally based on experience when designing either two-phase or three-phase separators.

The residence time approach for liquid-liquid separator design has been widely used in industry for years. However it is recognized that it has some serious limitations.<sup>13</sup>

- The typical approach of assuming equal residence times for both liquid phases may not be optimum as it is often easier to separate one phase from the other. Settling theory (Equation 7-1) quantifies this relative ease of separation as attributable to the lower viscosity of one phase

over the other. Dispersed droplets can move at higher velocities through low viscosity liquid and thus settling is more readily accomplished.

- Residence times do not take into account vessel geometry, i.e. 3 minutes residence time in the bottom of a tall, small diameter vertical vessel will not achieve the same separation performance as 3 minutes in a horizontal separator according to droplet settling theory.
- The residence time method does not provide any indication as to the quality of the separated liquids, e.g. amount of water in the hydrocarbon or the amount of hydrocarbon in the water. Droplet settling theory cannot do this either, but there may be empirical data available which can be correlated against droplet settling velocity to allow for approximate predictions in specific applications.
- The use of Stokes' Law correlations is not valid for very small droplets approaching the Brownian motion range. These services may require the use of specialized internals or electrostatic fields to promote coalescence.
- Residence time is one of many factors affecting separation performance. Other factors include height of liquid levels, length of separation section, and non-linear flow streams within the separator liquid sections.

## Dispersion Layer

If the concentration of the dispersed phase in the continuous phase is locally high, the dispersed phase droplets may settle to the interface faster than if they coalesce at the interface and form a dispersion band between the two phases, resulting in the inter-phase boundary being not well defined. In this case the coalescing step will be rate determining, over droplet settling. For this scenario, the dispersion layer must be considered when determining vessel size. This behavior is common for production separators with high water/hydrocarbon ratio, and some mixer-settler applications.

## Liquid-Liquid Coalescing Devices

Liquid-Liquid coalescers are internals used to accelerate the merging of many droplets to form a lesser number of droplets with a greater diameter. Elements of this type allow for efficient removal of smaller droplets, that otherwise would be difficult to capture by gravity settling alone. They also can provide a more compact settler design, for a given target droplet size. Typically the coalesced droplets are settled by gravity downstream of the coalescing elements, or by a secondary device followed by gravity separation. The preferred type of coalescer element depends on the type of emulsion to be separated, and the fouling nature of the fluid. The emulsion stability is a function of the upstream processing shear, and chemical addition. The more stable the emulsion, the finer the droplets.

A plate coalescer confines the droplet between parallel sheets or crimped packing sheets in order to reduce the distances a droplet must rise or fall, and provide multiple interface layers on which to coalesce. They also reduce the Reynolds number, and limit turbulence. Plate type coalescers are commonly limited to efficient removal of droplets above 50 microns minimum droplet size. Plates can be installed horizontally, or on angle to resist fouling. The settling mechanism in plates is often referred to as enhanced gravity separation.

A mesh type coalescer depends primarily on direct interception, where a multiplicity of wires or yarns collect fine droplets

as they travel in laminar flow around them. As the filament size is decreased, the mesh coalescer efficiency to remove smaller droplets is enhanced. Simple wire mesh coalescers may remove droplets down to 20 micron, while co-knits can be efficient down to 2 microns or less. Fiber cartridge element designs can be used to remove haze from fuel. Mesh elements units may require filtration upstream to remove solid contaminants, and cartridge units will definitely require filtration upstream of the process equipment. Coalescing mesh is also frequently used for applications where the concentration of one fluid is less than 5% of the total, as would be the case either following an upstream primary separator, at the outlet of a condenser or cooler in the process, or from storage.<sup>12</sup>

## SEPARATION STRATEGY AND PERFORMANCE REQUIREMENTS

### Separation Strategy

The ultimate separation for a particular separator, or in a process system, is often not achieved in a single step. An initial separation achieves bulk phase segregation then a secondary separation is provided for each of the bulk phase streams to obtain more purified phases. This is called progressive separation.

The principle of progressive separation is often utilized in a typical separator design. Within the vessel primary separation (e.g., inlet devices and gravity settling) roughly segregates the phases. Each phase still contains significant portions of the other phases. In secondary separation (e.g., mist eliminators and coalescers plus gravity) mist is removed from the gas phase, gas from the liquid phase, oil from water, and water from oil.

The principle of progressive separation can also apply to a process system where various levels of separation are performed in separate vessels arranged in series. Examples of this would be a slug catcher, an inlet separator, and a filter-separator all installed in the front of a natural gas treating facility for slug removal, liquid-gas separation, and final solids-mist separation.

### Performance Requirements

Ideally, a separator should yield a gas stream free of entrained liquid mist and a liquid stream containing no entrained gas bubbles. A three phase separator should, additionally, eliminate water from the oil stream and oil from the discharged water. In real-world process systems these phase separations are never complete and separator performance is measured against a specified allowable carryover of the contaminating phase.

The allowable carryover is determined by requirements of the downstream system or is often set based on customary practice. The treatment goals and the downstream needs should be scrutinized when determining the specified carryover limits. This will provide a perspective on how aggressive or how conservative to be when sizing the separator.

Not all separators have the same process requirements. For most, the critical issue is to minimize liquid carryover in the gas discharge line. For some, water quality may be critical. For others, the hydrocarbon stream water content must be controlled. In many cases the primary separation equipment cannot be effectively designed to meet all of the requirements and specialized equipment (i.e. filter-separators), must be used to remove remaining mist and solids.

## Liquid Carry-Over Specification for Gas-Liquid Separators

Usually the most critical carryover specification for separators is that of liquid entrainment in the gas outlet stream. The gas may be routed to a compressor, to downstream processing, or to a flare/vent. For example, severe mechanical damage will result if a significant volume of liquid is ingested into a compressor. In amine or glycol systems, uncontrollable foaming may occur if the solvent is contaminated by liquid hydrocarbons. Liquid carryover for an NGL recovery system can result in off-specification natural gas product, or substantial economic loss. Entrained liquid carried to a flare or vent poses potential fire hazards. These processes are normally protected by a gas scrubber to catch small amounts of separator carryover. Typical industry standard liquid carryover limits are often expressed in one of several ways. Examples of typical specifications for gas scrubbers with internal demisting devices are:

- 0.1 gal / MMSCF (absolute reference)
- Supplier guarantee based on % removal for a specified droplet size, (i.e.  $d_{95}$ , or 99% removal efficiency at 10 microns)
- 98% overall liquid recovery

For amine and glycol systems common industry practice is to limit solvent carryover to 0.1 gal/MMSCF. This may require a more complex mist eliminator design than a standard efficiency wire mesh mist eliminator.

It is not customary in most gas-liquid applications for the user to supply an inlet droplet average size and distribution to the device supplier. For these circumstances an absolute carryover specification quantity can not be provided. It is more common to require a % removal level, for a target micron size, which is consistent with the capabilities of the de-misting device employed. Proper specification of the device type and specific style is essential to the selection process. For critical applications, if an estimate of the average particle size and distribution estimate can be provided (i.e. based on a flow and entrainment model for the inlet piping), then an overall entrainment rate can be provided by the separation device supplier.

The gas compression industry does not use a universal standard for the upstream droplet size removal, or overall required droplet removal efficiency for scrubbers associated with this equipment. Experience has shown that excessive machine wear, and increased maintenance cost, typically result from poor scrubber design (i.e. wrong inlet device, uneven gas distribution), regardless of the de-misting device used.<sup>25</sup> Also, as the overall entrainment level increases, droplets can collect in the compressor inlet pipe, and the periodic flow of these coalesced droplets may result in long term wear on the machine. Liquid slug carryover may result in catastrophic machine failure.

## Gas Carry-Under Specification

The discharged liquid phase will typically contain gas bubbles too small to be removed in the separator. If gas carry-under is too high it may impact downstream operations. Carry-under of a few percent by volume is typically allowed for production separators, while minimal carry-under is allowable for most unit operations in the gas processing facility. A typical requirement for light hydrocarbons is minimal carry-under for gas bubbles 200 micron and larger. This is particularly important when the liquid is being pumped downstream of the separator, since pumps are only tolerant of dispersed dissolved gas to a limited extent. Gas volumes above 2% should be checked by the pump manufacturer.

**FIG 7-13**  
**Separator Configurations**

|                                                  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|--------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Vertical Two Phase Separators with Internals     | <ul style="list-style-type: none"> <li>• Vertical with no mesh pad</li> <li>• Vertical with mesh pad</li> <li>• Vertical with vane pack in horizontal flow</li> <li>• Vertical with vane pack in vertical flow</li> <li>• In-line vane pack (in-line separator)</li> <li>• Cyclone</li> <li>• Axial flow multi-cyclone</li> <li>• Conventional (reverse flow) multi-cyclone</li> <li>• Combination configuration (e.g., vertical flow flooded mesh/ vane)</li> <li>• Combination configuration (e.g., horizontal flow flooded mesh/ vane)</li> <li>• Combination configuration (e.g., flooded mesh/ multi-cyclone bank)</li> </ul> |
| Horizontal Two Phase Separators                  | <ul style="list-style-type: none"> <li>• Horizontal with no mesh pad</li> <li>• Horizontal with vertical mesh pad</li> <li>• Horizontal with horizontal mesh pad in box under outlet nozzle</li> <li>• Horizontal with vertical vane pack</li> <li>• Horizontal with vane pack canted between vertical and horizontal</li> <li>• Horizontal with inlet cyclones and/or outlet cyclones</li> </ul>                                                                                                                                                                                                                                  |
| Liquid-Liquid and Three Phase Separators         | <ul style="list-style-type: none"> <li>• Gravity separator (no baffles or internals)</li> <li>• Separator with mesh coalescer</li> <li>• Separator with vane or plate coalescer</li> <li>• Three phase separator with single overflow baffle</li> <li>• Three phase separator with overflow-underflow baffle</li> <li>• Three phase separator with water boot</li> <li>• Complex multi-baffle separators</li> <li>• Vertical three phase separator</li> </ul>                                                                                                                                                                      |
| Cyclonic Two and Three Phase Separators          | <ul style="list-style-type: none"> <li>• Conventional reverse flow cyclonic separator</li> <li>• Advanced compact cyclonic separators</li> <li>• Inline cyclonic devices</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                |
| Devices with Cartridges                          | <ul style="list-style-type: none"> <li>• Filter separator</li> <li>• Gas Coalescing filter (gas-liquid)</li> <li>• Coalescing filter (gas-liquid-solids)</li> <li>• Dust filter</li> <li>• Liquid Coalescer</li> <li>• Liquid-solids cartridge filter</li> <li>• Liquid solids bag filter</li> </ul>                                                                                                                                                                                                                                                                                                                               |
| Specialized Gas-Liquid Separators                | <ul style="list-style-type: none"> <li>• Wellhead Separator</li> <li>• Test Separator</li> <li>• Vessel type slug catcher</li> <li>• Harp type slug catcher</li> <li>• Flare K.O. drums</li> <li>• Specialized cyclone separators</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                       |
| Specialized Oil Treating Coalescing Separators   | <ul style="list-style-type: none"> <li>• Heater-Treater</li> <li>• Desalter</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| Specialized Water Treating Coalescing Separators | <ul style="list-style-type: none"> <li>• Gunbarrel tank</li> <li>• Water hydrocyclone</li> <li>• CPI Separator</li> <li>• API Separator</li> <li>• Dissolved gas flotation unit</li> <li>• Walnut shell filter</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                          |

## Water-in-Hydrocarbon Specification

For three phase separation the water-in-oil specification depends on the operation downstream of the separator. If oil leaving the separator is to meet transport specifications or is going to a tower or heating process the performance is usually more critical. If the separator feeds in-plant treating, the water-in-oil specification is usually less critical. For primary separators, with no emulsions, the typical separation results in 0.1 to 0.5 Vol.% water in hydrocarbon. For other production service the value may be higher or lower depending on the destination.

## Oil-in-Water Specification

Oil-in-water carryover may be specified or left as a consequence of a specified water phase sizing. Produced water and process water are ultimately disposed of by injection, disposal to a water way, or further treatment. Direct disposal options

**FIG 7-14**  
**General Gas Separation Selection**

| Equipment Type           | Contaminant Removed | Micron Rating Achievable | Pressure Drop Clean & Wet | Relative Operating Cost |
|--------------------------|---------------------|--------------------------|---------------------------|-------------------------|
| Separator with internals | Liquids             | 3-40                     | Low 0.1 psi-1.5 psi       | Low to higher           |
| Filter – Separator       | Liquids & Solids    | 1 micron                 | 2 psi or less             | Higher                  |
| Gas Coalescer            | Liquids & Solids    | 0.3 micron               | 2 psi                     | Highest                 |
| Dry Gas Filter           | Solids              | Various                  | 2 psi or less             | Higher                  |

require relatively clean water (typically 15-50 ppm<sub>v</sub> oil) which often necessitates further treatment of the water discharged from a separator. Permissible values for discharge depend on local regulations. A specified oil-in-water limitation in the separator discharge reflects the maximum carryover for feeding the water treatment equipment.

**FIG. 7-15**  
**Factors that Determine Vessel Orientation**

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

**FIG. 7-16**  
**Vertical Gas-Liquid Separator Comparison Chart**

| Separator Type:                  | No Demisting Internals | Mesh Pad  | Vert. Vane Pack | Horiz. Vane Pack | In-line Vane Pack | Axial Flow Multi-Cyclone | Horiz. Flood Mesh/Vane | Vert. Flood Mesh/Vane | Flood Mesh/ Multi-Cyclone |
|----------------------------------|------------------------|-----------|-----------------|------------------|-------------------|--------------------------|------------------------|-----------------------|---------------------------|
| <b>Gas Handling</b>              |                        |           |                 |                  |                   |                          |                        |                       |                           |
| Capacity                         | Low                    | Moderate  | High            | Very High        | Very High         | Very High                | Very High              | Very High             | Very High                 |
| Turndown Capability              | ∞                      | 4:1       | 3:1             | 3:1              | 3:1               | 2:1                      | 4:1 or higher          | 4:1 or higher         | 4:1 or higher             |
| <b>Liquid Removal Efficiency</b> |                        |           |                 |                  |                   |                          |                        |                       |                           |
| Efficiency Overall               | Low                    | Very High | Moderate        | Low/Mod          | Low/Mod           | High                     | Moderate               | High                  | High                      |
| Efficiency – Fine Mist           | Very Low               | Very High | Moderate        | Moderate         | Moderate          | High-Very high           | Very High              | Very High             | Very High                 |
| <b>Liquid Handling Capacity</b>  |                        |           |                 |                  |                   |                          |                        |                       |                           |
| Slugs                            | High                   | High      | High            | Very High        | Very Low          | High                     | High                   | High                  | High                      |
| Droplets                         | High                   | High      | Moderate        | Moderate         | Low               | High                     | High                   | High                  | High                      |
| <b>Fouling Tolerance</b>         |                        |           |                 |                  |                   |                          |                        |                       |                           |
| Particulate                      | Very High              | Low       | Moderate        | Moderate         | Moderate          | Moderate                 | Low                    | Low                   | Low                       |
| Fouling Material                 | Very High              | Very Low  | Moderate        | Moderate         | Moderate          | Moderate                 | Low                    | Low                   | Low                       |
| Pressure Drop                    | Very Low               | Very Low  | Low             | Low              | Low               | High                     | Low                    | Low                   | High                      |