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KLM Technology Group #03-12 Block Aronia, Jalan Sri Perkasa 2 Taman Tampoi Utama 81200 Johor Bahru	<b>Kolmetz Handbook          of Process Equipment Design</b>  <b>Section Two: Engineering Systems          Design Group</b>  <b>GAS PLANT SLUG CATCHER          SELECTION AND SIZING</b>  <b>(ENGINEERING DESIGN GUIDELINE)</b>	Co Author: Rev 01 Reni Mutiara Sari  Editor Author Karl Kolmetz

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## INTRODUCTION

### Scope

A multi-phase flow pipeline is intended for transporting the gas and liquid phases simultaneously from a production field to a processing unit. A gas plant slug catcher may be situated at the end of the pipeline to separate the phases and to provide temporary storage for the liquid received. There are different modes under which liquid can be produced from the pipeline. These include: the continuous liquid flow production mode under normal steady flow conditions; the intermittent or transient liquid production mode occurring when flow rates are varied; and the pigging or sphering mode when liquid is displaced from the pipeline into the slug catcher in a relatively short time.

These occasionally very large volumes of liquids encountered must be handled and stored as they emerge from the pipeline, preferably without any reduction in velocity, which would be reflected in the gas production. For this reason, a liquid-receiving facility known as a slug catcher is connected to a two phase pipeline<sup>[9]</sup>.

The initial gas-liquid separation occurs in a slug catcher. Slug catchers are critical because downstream gas processing units rely on a continuous gas stream free of liquids, even when surges of liquid enter the plant. A slug catcher is a gas-liquid separator sized to hold the biggest slug a plant will experience. Depending upon slug catcher design, inlet receiving handles just slugs or combines slug catching with liquid storage<sup>[5]</sup>.

The appropriate design of the slug catcher avoids problems at the receiving terminals. In order to prevent the acceleration of the gas/liquid mixture, the inlet diameter of the pipes entering the slug catcher should be the same as that of the pipeline. Normally the slug catcher is made up of a series of pipes that are parallel and inclined in order to give the hold-up volume for the liquid<sup>[11]</sup>.

Two steps to determine the slug catcher to be utilized are slug catcher selection and slug catcher sizing. Selection of slug catcher includes multiphase separator selection that based on function and liquid volume. The important of slug catcher hold-up volume and gas handling or terminal velocity are explained.

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The theory for the slug catcher selection and sizing consists of gravity separation, two phase and three phase separators considerations. Multiple-pipe slug catcher design procedure and the instruments that typically installed in slug catcher are also summarized in this guideline.

## INTRODUCTION

### General Consideration

The slug catcher is mainly made up of two different compartments: the first one includes the multiphase separator under steady flow conditions while the second consists of the storage where the received liquid is accumulated under operating conditions. There are two and three phase separators which are described as follow.

#### I. Two Phase Separator

The slug catcher is a separator, where separation typically occurs between the heavy liquid hydrocarbons and the gaseous lighter ends i.e. the gas or vapor is separated from the liquids. The vapor – liquid separator is described as follow.

##### A. Vapor-Liquid Separator

Vapor-liquid separator is one of the most common types of process equipment in natural gas processing plants. A vapor-liquid separator is a vessel into which a liquid and vapor mixture is fed and wherein the liquid is separated by gravity, falls to the bottom of the vessel, and is withdrawn. The vapor travels upward at a design velocity which minimizes the entrainment of any liquid droplets in the vapor as it exits the top of the vessel.

A vapor-liquid separator might consist simply of an empty vessel, which causes the fluid velocities in the entering pipe to be reduced by enlarging the cross-sectional area of flow. Usually, however the separator includes internal parts, to promote separation of the process, such as <sup>[12]</sup>:

1. Primary separation section (entrance): for separating the bulk of the liquid from the gas. It is desirable to remove the liquid slugs and large droplets of liquid quickly from the gas stream, and to remove gas from the liquid.

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2. Secondary separation section: for removing smaller particles of liquid by gravity settling depends to a large extent on the decreased gas velocity and reducing the turbulence of gas.
3. Liquid separation section (or the liquid accumulation section): for removing gas bubbles which may be occluded with the liquid, and for sufficient storage of the liquid to handle the slugs of liquid anticipated in routine operation.
4. Mist extractor or eliminator section (mist pad): for removing from the gas entrained drops of liquid, which did not separate in the secondary separation section. Mist extractor might be used to decrease the amount of entrained liquid in the gas and to reduce diameter of the vessel. Thickness of mist eliminator is typically 6 inch.
5. Vortex breaker (in the bottom of the vessel): prevents potential pump suction problems if a pump is used to remove collected liquids. Provide vortex breakers on outlet nozzles that are piped to a pump and where flow continuity at minimum liquid level is critical. Hydrocarbon liquid outlets should project 4 to 6 inches above the drum bottom if water is likely to be present and the water will interfere with downstream processing.

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Separator vessel orientation may be vertical or horizontal. Vertical separators are most commonly used when the liquid-to-gas ratio is low or gas flow rates are low. They are preferred offshore because they occupy less platform area. Whereas, horizontal separators are favored for large liquid volumes or if the liquid-to-gas ratio is high. Lower gas flow rates and increased residence times offer better liquid dropout. The larger surface area provides better degassing and more stable liquid level as well<sup>[5]</sup>.

Following figures are two phase separators in vertical and horizontal.

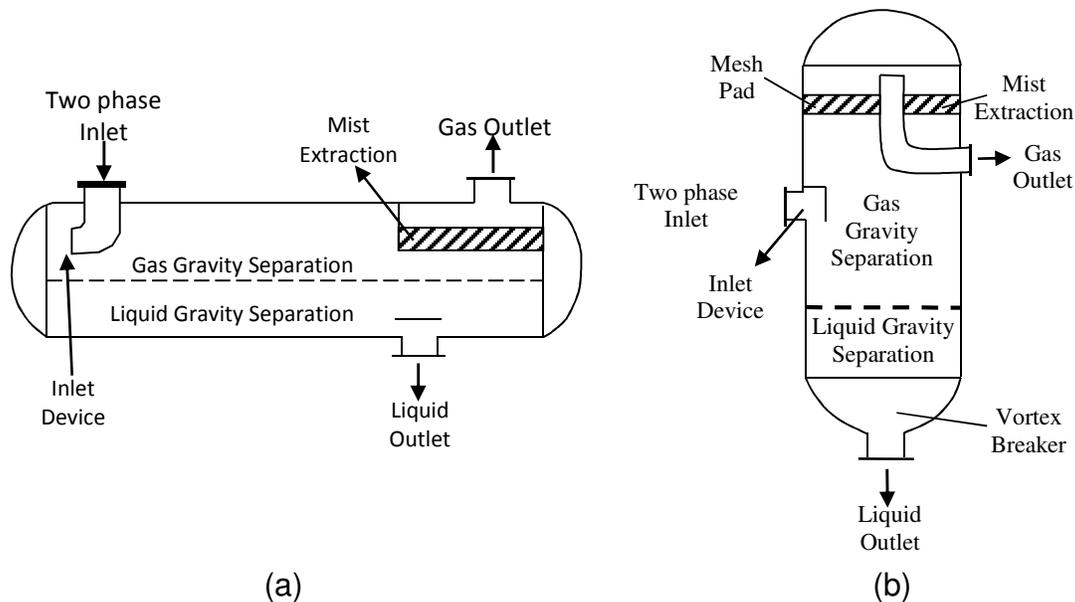


Figure 1: internal parts of (a) vertical separator and (b) horizontal separator

Separators may be designed with or without mist eliminator pads and may also have inlet diverters. Some separators may also have proprietary impingement or settling internals.

An inlet diverter produces the initial gross separation of liquid and vapor, as the sudden change in momentum occurs when the fluid enters the separator and hit it. Commonly, the inlet diverter contains a down comer that directs the liquid flow below the oil or water interface. The inlet diverter assures that little gas is carried with the liquid.

Some functions of inlet diverter are:

- Reduces momentum of inlet stream

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- Provides primary (bulk) separation of gas and liquid
- Enhances flow distribution of gas and liquid phases
- Prevents droplet shattering and re-entrainment of bulk liquid phases
- Stable liquid level control and reduced foaming

Based on comparison of the performance of different inlet diverter in similar conditions, it states that a separator vessel would always be necessary to install a sophisticated inlet diverter such as vane type distributors or cyclones. The efficiency of their inlet diverters are 0.95 and more than 0.95 for bulk liquid removal<sup>[13]</sup>.

The impingement or settling internal might be added to optimized separation process. As the descriptive name suggests, the impingement separator allows the particle to be removed to strike some type of surfaces. There are basically three construction types for impingement separator: wire mesh, plates (curved, flat, or special shaped), and packed impingement beds.

## II. Three Phase Separator

### A. Vapor-Liquid-Liquid Separator

Three phase separation is commonly applied when there are water, liquid hydrocarbon and hydrocarbon gases in the process stream. As with two phase design, three phase units can be either vertical or horizontal.

Vertical vessel is mainly applied when there is a large amount of vapor to be separated from a small amount of the light and heavy fluid (less than 10-20% by weight). Horizontal vessels are most efficient where large volumes of total fluid and large amounts of dissolved gas are present with the liquid. An example for vertical vessels is the compressor suction drums while good representative of horizontal vessel is the spent caustic de-oiling drum.

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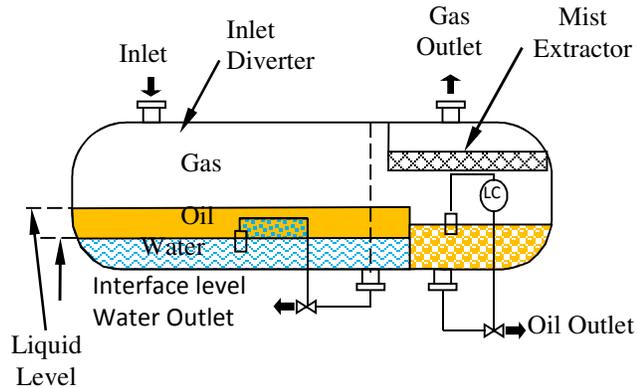


Figure 3: horizontal 3-phase separator

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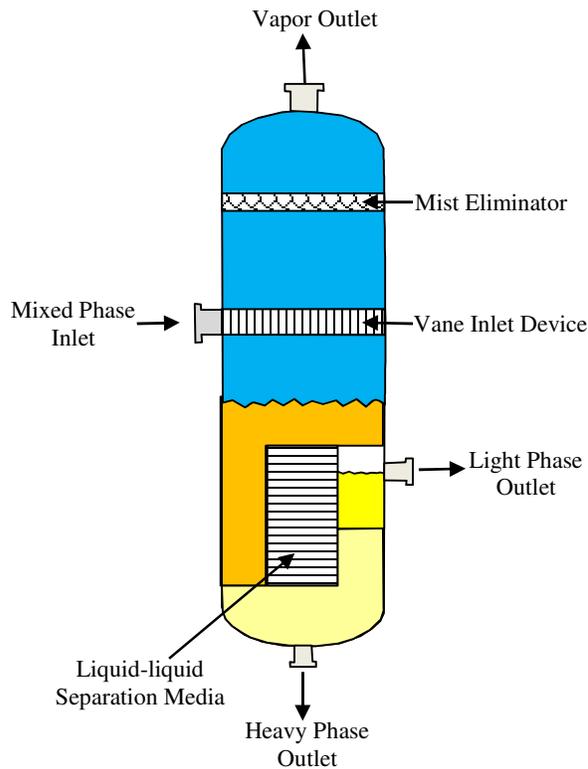


Figure 4: vertical 3-phase separator

The three phase separation vessel commonly contains four major sections as listed below:

- a. The primary separation section used to separate the main portion of free liquid in the inlet stream
- b. The secondary or gravity section designed to utilize the force of gravity to enhance separation of entrained droplets.
- c. The coalescing section utilizes a coalescer or mist extractor. The normal application is using a knitted wire mesh pad on top of vessel.
- d. The sump or liquid collection section acts as receiver for all liquid removed from gas in the primary, secondary, and coalescing section.

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A vane-inlet device might be used in this separator to gradually reduce the inlet momentum and evenly distribute the gas phase across the vessel diameter. Such device can also act as the first-stage gas-liquid separation. In the gas-liquid portion of the vessel, a wire-mesh mist eliminator provides high separation efficiency.

For the liquid-liquid separation in the bottom of the drum, the first-stage is typically some type of enhanced-gravity separation media. If very high separation is required, adding a second “polishing” stage provides the ability to remove the last remnants of entrainment.

### III. Types of Slug Catcher

There are basically two types of slug catchers, the vessel and multiple-pipe types that can be described as follow.

#### A. Vessel Type Slug Catcher

Vessel type slug catcher is simply gas–liquid separator that combine slug catching with liquid storage. They are usually employed where operating pressures are relatively low. The vessel type can range from a simple to a more complicated knock-out vessel which is mainly used for limited plot sizes such as offshore platforms due to its small size. This type is also normally used or crude-oil stream, where foaming sometimes emerges as a major problem.

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The vessel type slug catcher is illustrated as shown in figure 5.

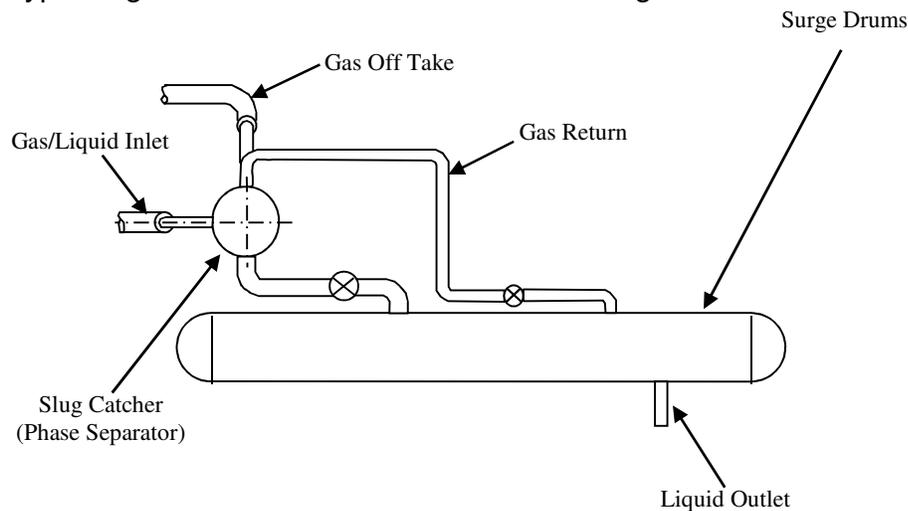


Figure 5 : vessel type slug catcher with separate surge drums

## B. Multiple-pipe Slug Catchers

The multi-pipe slug catcher is made up of a liquid and gas separation entry slot and a series of parallel tilted bottles where the liquid is stored. However, this design requires special pigs to accommodate the change in line size. Multiple-pipe slug catchers have been widely applied in facilities processing a gas condensate stream. Multiple-pipe slug catcher is mainly used when liquid volume is larger than  $100 \text{ m}^3$ <sup>[9]</sup>. The multiple-pipe slug catcher consist of several components<sup>[11]</sup> :

### a. Inlet section

In inlet section, gas-liquid of end of pipeline enters to inlet section to obtain an even distribution. To create such condition, the flow should be passing splitter and collected into inlet header before proceeding to the down comers. Down comers are inclined downward whenever possible to occur stratified two-phase flow and then flow to bottle section.

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**b. Bottle section**

The bottle section of the slug catcher, including primary and/or secondary bottles. The primary bottles encompasses the gas-liquid separation just upstream the first gas risers. The storage of liquid takes place downstream the riser. The secondary bottles are designed to eliminate short inconsistencies in gas flow. They act as a gas reservoir and allow for co current gas and liquid flow in the system. Liquid from the primary bottles equalize into the secondary bottles where the displaced gas is free to flow into the process without restriction due to counter flow<sup>[7]</sup>. This section also comprises a change in elevation between the gas risers and the storage section that allows a clear distinction between liquid and gas phases.

**c. Gas outlet section**

This section includes the gas risers, the gas outlet headers and the gas outlets. Ensuring a flow of gas out of the unit is the main function of a gas riser along with the prevention from liquid carryovers in case of large volumes of liquid passing through the lower region of the riser.

**d. Liquid outlet section**

For the liquid outlet, it should be of the same diameter as the bottles or minimum 75% of it in order to be able to handle the large liquid volumes without blocking the passage. The gas carry-under is to be taken care of or avoided by having the liquid outlet header lower than the lower end of the bottle<sup>[11]</sup>. A schematic of this type appears in Figure 6.

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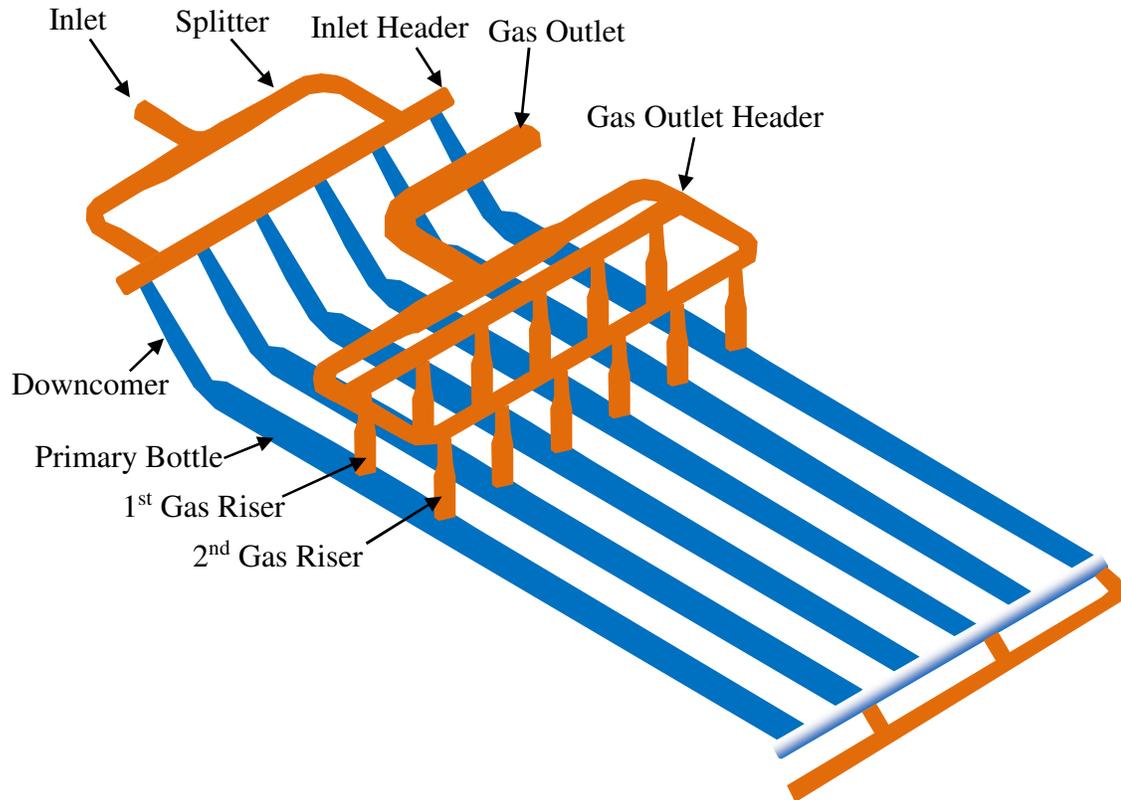


Figure 6: multiple-pipe slug catcher

In a slug catcher, the separation of liquid from the gas can occur in different manners, including:

1. Stratification in the inlet manifold, down comers and primary bottles
2. Droplet settling in the primary bottles
3. Deposition in bends and primary bottles
4. Tee-junction separation at entry into a gas riser<sup>[9]</sup>

For inclined slug catchers, the goal is usually similar to provide the proper liquid hold-up volume, although the equations may be more complex depending on how steep the inclination is. If the slug catcher is mounted fairly steeply, the volume can be estimated by calculating the liquid holdup as a vertical vessel. If the inclination is gradual, the horizontal vessel calculation can be used for estimation purposes<sup>[11]</sup>.

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#### IV. Pigging

Pigging is the process of forcing a solid object through a pipeline. The functions of pigging are provided in the lines to allow for pipeline cleaning and inspection, which are likely to be required during commissioning. In many instances pipelines are pigged to reduce pressure drop by lowering liquid hold-up volumes. In addition, it is also beneficial for reducing slug catcher size and reducing corrosion from any free water and other contaminants in the line.

Launching a pig into the system will remove the majority of liquid and will end up in the slug catcher at the receiving facilities. Pigging can affect greatly the regularity of the slug emergence to the slug catcher aside from the natural slug flow. The design basis for pigging frequency will have a significant impact on slug sizes from pigging and the required slug catcher size. Process of pigging can be shown in figure 7.

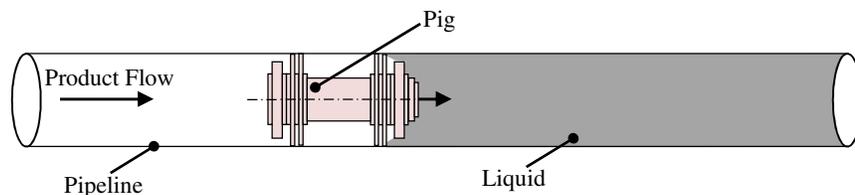


Figure 7: pigging process

#### V. Liquid Hold-Up Volume

The liquid hold up calculation is very often the key element in sizing slug catcher facilities. If frequent pigging is not used on the line, and the pipeline is allowed to achieve steady state operation in regard to liquid hold up, the slug volume expected should be estimated as the liquid hold up of the entire pipeline. For long pipelines (longer than 5 miles), the liquid hold-up calculation and bypass pig will be important in determining if frequent pigs should be run in the pipe to avoid having large slug volumes. In most cases with a shorter pipeline, the slug catcher should be sized for at least the liquid hold-up in the pipeline.

To reduce liquid hold up requirements in the slug catcher, it may be advantageous to install an intermediate vessel (e.g. condensate feed drum) for additional liquid surge capacity. The intermediate vessel typically operates at a lower pressure than the slug catcher and it therefore reduces the cost of liquid slug volume capacity. The offset to

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this cost savings is the flash gas handling equipment such as a separate flash gas compressor<sup>[1]</sup>.

## VI. Fluid Flow Regime

Several multiphase flow regimes take place in horizontal pipelines. Phase separation usually occurs when the gravity effect is perpendicular to the pipe axis. Operating in these flow regimes also will help minimize pigging frequency and slug catcher capacity requirements. There are seven flow regimes that represented as shown in figure 8.

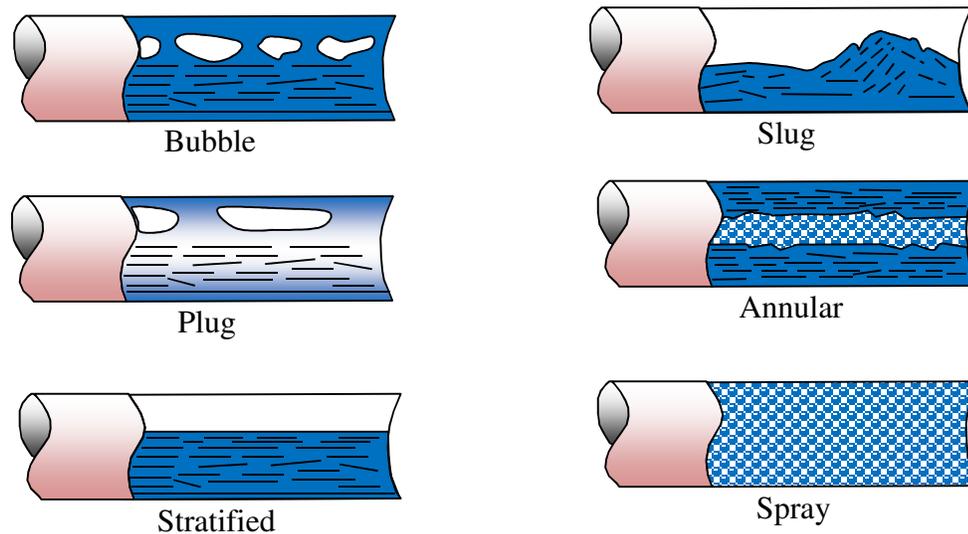


Figure 8: multiphase flow regimes

The types of flow regimes can be described as the vapor rate increases as follow<sup>[1]</sup> :

1. Bubble flow : bubbles dispersed in liquid with vapor and liquid velocities are approximately equal.
2. Plug flow : plugs of liquid flow followed by plugs of gas. The bubbles coalesce, and alternating plugs of vapor and liquid flow along the top of the pipe with liquid remaining the continuous phase along the bottom.

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3. Stratified flow : liquid and gas flow in stratified layers. The fraction occupied by each phase remains constant.
4. Wavy flow : gas flows in top of pipe section, liquid in lower section and the resulting friction at the interface forms liquid waves.
5. Slug flow : slugs of gas bubbles flowing through the liquid. It is formed when the liquid waves grow large enough to bridge the entire pipe diameter and the stratified flow pattern breaks down.
6. Annular flow : liquid flows in continuous annular ring on pipe wall, gas flows through center of pipe.
7. Spray flow : gas and liquid dispersed. When the vapor velocity in annular flow becomes high enough, all of the liquid film is torn away from the wall and is carried by the vapor as entrained droplets.

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## DEFINITION

**Accumulators-** These are storage tanks following distillation column condensers. For partial condensers, this flow may be a mixture of vapor and liquid. The outlet flow may be regulated by a level controller in order to avoid the tank either flooding (liquid out the top) or going dry (vapor out the bottom).

**Coalescer -** A mechanical process vessel with wettable, high-surface area packing on which liquid droplets consolidate for gravity separation from a second phase (for example gas or immiscible liquid).

**Demister Mist Extractor-** A device installed in the top of scrubbers, separators, tray or packed vessels, etc. to remove liquid droplets entrained in a flowing gas stream.

**Disengaging Height-** The height provided between bottom of the wire-mesh pad and liquid level of a vapor-liquid separator.

**Hold-Up Time-** A time period during which the amount of liquid separated in a gas-liquid separator is actually in the vessel for the purpose of control or vapor separation.

**Knock-Out-** A separator used for a bulk separation of gas and liquid.

**Line Drip-** A device 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.

**Manifold -** A pipe with one or more inlets and two or more outlets, or vice versa.

**Mesh-** The "mesh count" (usually called "mesh"), is effectively the number of openings of a woven wire filter per 25 mm, measured linearly from the center of one wire to another 25 mm from it.

**Pigging -** Procedure of forcing a solid object through a pipeline for cleaning or other purposes.

**Residence time -** The time period for which a fluid will be contained within a specified volume.

**Slug catcher -** Separator that is designed to separate intermittent large volumes of liquids from a gas stream.

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**Surge time** - The time it takes for the liquid level to rise from normal (NLL) to maximum (HLL) while maintaining a normal feed without any outlet flow.

**Terminal Velocity or Drop-Out Velocity**- The velocity at which a particle or droplet will fall under the action of gravity, when drag force just balances gravitational force and the particle (or droplet) continues to fall at constant velocity.

**Underflow** - The stream containing the remaining liquid and the coarser solids, which is discharged through a circular opening at the apex of the core of a hydrocyclone is referred to as "underflow".

**Vapor Space**- The volume of a vapor liquid separator above the liquid level.

## NOMENCLATURE

$A_D$	= downcomer cross-sectional area, ft <sup>2</sup>
$A_{NLL}$	= normal and high liquid level, ft <sup>2</sup>
$A_{LL}$	= the cross-sectional area of the light liquid, ft <sup>2</sup>
$A_V$	= vapor disengagement area, ft <sup>2</sup>
$C'$	= drag coefficient, dimensionless
$D$	= vessel diameter, ft or in
$D_B$	= heavy liquid boot diameter, ft
$d_N$	= nozzle diameter, ft
$D_p$	= droplet diameter, ft or microns
$D_{VD}$	= vapor disengagement diameter, ft
$g$	= gravitational constant, ft/s <sup>2</sup>
$H_A$	= liquid level above baffle, which is 6 inch (minimum)
$H_{BN}$	= liquid height from above baffle to feed nozzle, ft
$H_D$	= disengagement height, ft
$H_H$	= holdup height, ft
$H_{LL}$	= high liquid level height, ft
$H_{LLL}$	= low liquid level height, ft
$H_R$	= height from light liquid nozzle to baffle, in
$H_S$	= surge height, ft
$H_T$	= total height, ft
$H_V$	= minimum height of the vapor disengagement area, ft
$H_W$	= weir height, ft
$L$	= minimum length to accommodate the liquid holdup/surge, ft

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- $L_{min}$  = length required for vapor-liquid disengagement, ft  
 $M$  = fraction of vertical area filled with liquid, dimensionless  
 $Q_{HL}$  = heavy liquid volumetric flow rate, ft<sup>3</sup>/min  
 $Q_m$  = Mixture volumetric flow rate, ft<sup>3</sup>/s  
 $Q_L$  = liquid volumetric flow rate, ft<sup>3</sup>/min  
 $Q_{LL}$  = light liquid volumetric flow rate, ft<sup>3</sup>/min  
 $Q_V$  = vapor volumetric flow rate, ft<sup>3</sup>/s  
 $Re$  = reynold number, dimensionless  
 $t_{HL}$  = settling time for the heavy liquid droplets, min  
 $t_{LL}$  = settling time for the light liquid droplets, min  
 $T_H$  = holdup times, min  
 $T_S$  = surge times, min  
 $V_H$  = holdup volume, ft  
 $V_S$  = surge volume, ft  
 $V_T$  = terminal velocity, ft/s or in/min  
 $V_{VA}$  = actual vapor velocity, ft/s

### Greek Letter

- $\lambda$  = Mixture liquid fraction  
 $\dot{m}_L$  = mass flow rate of liquid, lb/h  
 $\dot{m}_{LL}$  = light liquid mass flow rate, lb/h  
 $\dot{m}_{HL}$  = heavy liquid mass flow rate, lb/h  
 $\dot{m}_V$  = mass flow rate of vapor, lb/h  
 $\rho_m$  = Mixture density, lb/ft<sup>3</sup>  
 $\rho_{HL}$  = heavy liquid density, lb/ft<sup>3</sup>  
 $\rho_L$  = liquid density, lb/ft<sup>3</sup>  
 $\rho_{LL}$  = light liquid density, lb/ft<sup>3</sup>  
 $\rho_V$  = vapor density, lb/ft<sup>3</sup>  
 $\Phi$  = liquid drop time, s  
 $\theta_{HL}$  = residence time of heavy liquid phase, min  
 $\theta_{LL}$  = residence time of light liquid phase, min

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## THEORY

### I. Gravity Separation

The main separators are gravity type. This type tends to use gravity as the dominant force. Gravity settling requires low gas velocities with minimal turbulence to permit droplet fallout.

Gravity separations also depend essentially on the density differences of the gas, solid, or liquids present in the mixture. The particle (droplet) size of the dispersed phase and the properties of the continuous phase are also factors with the separation motivated by the acceleration of gravity.

Liquid droplet drop out when gravitational pull is greater than the drag force of the flowing fluids around the droplet. These forces can be described mathematically using the terminal or finite-settling velocity calculation,

$$V_T = \sqrt{\frac{4gD_p(\rho_L - \rho_V)}{3\rho_V C'}} \quad \text{Eq. (1)}$$

Where,

- $V_T$  = terminal velocity, ft/s
- $D_p$  = droplet diameter, ft
- $g$  = gravitational constant, 32,17 ft/s<sup>2</sup>
- $\rho_L$  = liquid density, lb/ft<sup>3</sup>
- $\rho_V$  = vapor density, lb/ft<sup>3</sup>
- $C'$  = drag coefficient, dimensionless

The drag coefficient ( $C'$ ) is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid. It is always associated with a particular surface area. For the purpose of this equation, particle shape (droplet) is considered to be a solid, rigid sphere. This value also depends on the Reynolds number of the flowing fluid.

$$Re = \frac{1.488D_p V_T \rho_V}{\mu} \quad \text{Eq. (2)}$$

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Where,

Re = reynold number, dimensionless

$\mu$  = viscosity, cP

Iteration is needed to solve this problem since the terminal velocity ( $V_T$ ) is involved in both equations. Thus, the simplified equation is presented to avoid trial and error solution.

$$C'(Re)^2 = \frac{(0.95) \cdot (10^8) \rho_V D_p^3 (\rho_L - \rho_V)}{\mu^2} \quad \text{Eq. (3)}$$

Values of the drag coefficient as a function of the product of drag coefficient ( $C'$ ) times the Reynolds number squared are presented in Figure 9.

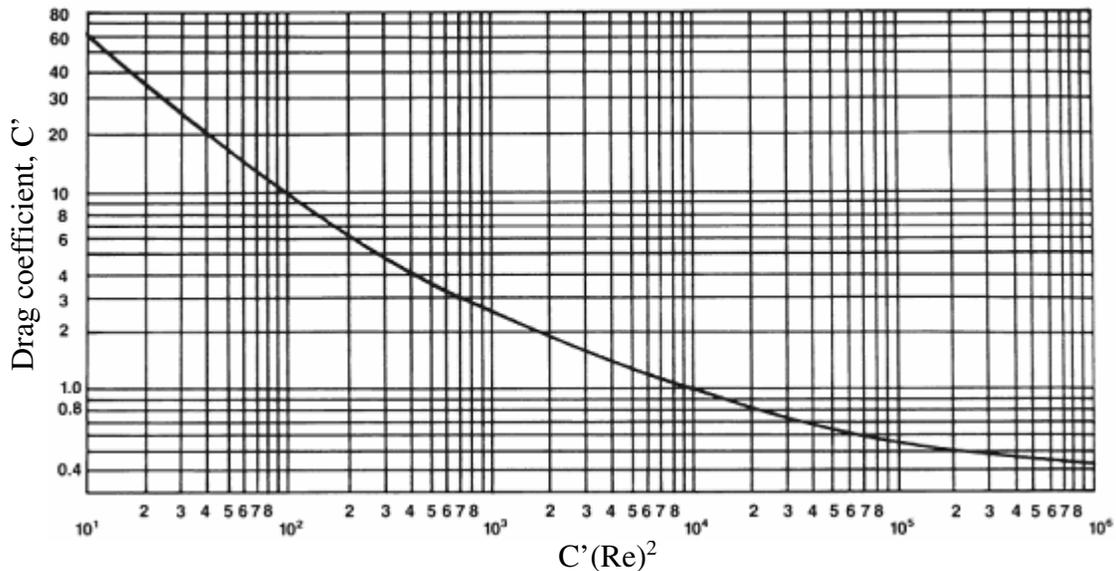


Figure 9: Drag coefficient for rigid spheres

Depending on Reynolds numbers, terminal velocity could be determined by several laws:

1. Stokes' Law

Stokes' Law is commonly applied at low Reynolds number (<2).

$$C' = 24 Re^{-1} \quad \text{Eq. (4)}$$

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Thus, Eq. (1) could be expressed as:

$$V_T = \frac{1,488 \text{ g } D_p^2 (\rho_L - \rho_V)}{18\mu} \quad \text{Eq. (5)}$$

The droplet size can be determined by

$$D_p = K_{CR} \left[ \frac{\mu^2}{\text{g } \rho_V (\rho_L - \rho_V)} \right]^{0.33} \quad \text{Eq. (6)}$$

use a value of 0.025 for  $K_{CR}$

## 2. Intermediate Law

This law is applied for Reynolds number between 2 and 500.

$$C' = 18.5 \text{ Re}^{-0.6} \quad \text{Eq. (7)}$$

Thus the terminal settling velocity is determined as

$$V_T = \frac{3.49 \text{ g}^{0.71} D_p^{1.14} (\rho_L - \rho_V)^{0.71}}{\rho_V^{0.29} \mu^{0.43}} \quad \text{Eq. (8)}$$

The droplet diameter can be found using a value of 0.334 for  $K_{CR}$  in Eq. (6).

## 3. Newton's Law

Newton's Law is applicable for a Reynolds number range of approximately 500-200,000. Use value of 0.44 for drag coefficient ( $C'$ ), thus the terminal velocity is

$$V_T = 1.74 \sqrt{\frac{\text{g } D_p (\rho_L - \rho_V)}{\rho_V}} \quad \text{Eq. (9)}$$

For the Newton's Law region, the upper limit to the Reynolds number is 200,000 and  $K_{CR} = 18.13^{[4]}$ .

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The main purpose of this process is to settle out droplets of entrained liquid from gas. Factors that affect the settling rate of these droplets are:

1. Droplet size; big droplets settle faster than little droplets.
2. Density of vapor; the less dense the vapor the faster the droplet settling rate.
3. Density of liquid; the more dense the liquid droplets, the faster the droplet settling rate.
4. Velocity of vapor; the slower the vertical velocity of the vapor, the faster the settling rate.
5. Viscosity of the vapor; the lower the vapor viscosity, the faster the settling rate.

## II. Retention Time Method

Sizing or specifying vessel slug catcher might be presented using retention-time method and drop-settling method.

### A. Gas-Liquid Separation

Specifying the liquid-phase retention time and the height of the gas-liquid interface provides the following sizing equation for horizontal cylindrical separators<sup>[8]</sup>.

$$\frac{\pi}{4} D^2 M L_{\text{eff}} = Q_L r_t \quad \text{Eq. (10)}$$

Where,

- D = vessel diameter, ft
- M = fraction of vertical area filled with liquid, dimensionless
- L<sub>eff</sub> = length of vessel, ft
- Q<sub>L</sub> = volumetric flow rate, ft<sup>3</sup>/min

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