Gravity Separation: A Separation Free of Charge!

In the science of separation, gravity separation holds a paramount position. Separations based on gravity are the default choice for the partitioning of different phases with different densities.

The importance of gravity separation lies in its driving force: *universal gravity*.

Universal gravity is a force which is available everywhere, has no chance of failure (no need for back-up systems), and it is completely free.

APPLICATIONS:

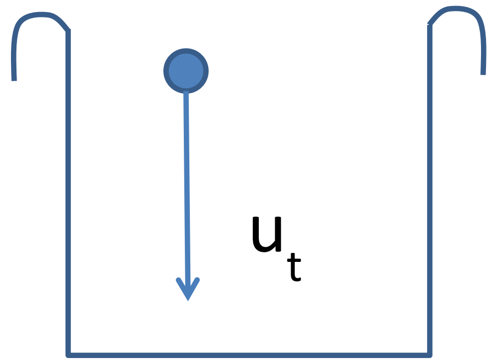
		Dispersed phase		
		Solid	Liquid	Gas/Vapour
Continuous Phase	Solid	NA	NA	NA
	Liquid	Water Treatment, Crystallizer,	Liquid Extraction, Liquid-Liquid separation	Aeration
	Gas/vapour	Air Pollution	Evaporator, Demister	NA

EXAMPLES:

		Dispersed phase		
		Solid	Liquid	Gas/Vapour
Continuous Phase	Solid	NA	NA	NA
	Liquid	Water Clarification	Decanters, Oil/water removal, FWKO, Skim tank, API Gravity Separator	Bubbles in liquid: Very quick separation Degassing Chamber
	Gas/vapour	Settling Chamber,	Scrubber(Knock drum), Compressor suction scrubber, Steam separator, Mist Extractors, Oil from gas(oil fields), Water from gas(gas fields), Volatile fractions from crude oil	NA

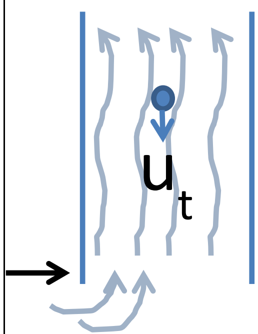
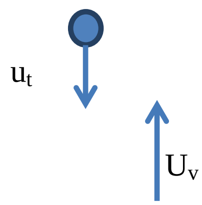
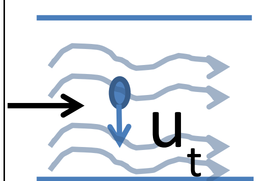
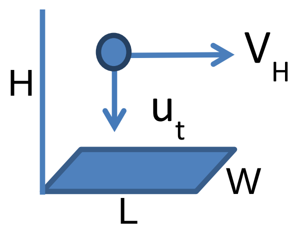
PRINCIPLE OF GRAVITY SEPARATION:

Gravity separation is based on the falling velocity of a heavier phase in dispersed mode, or the rising velocity of a lighter phase in dispersed mode. The schematics below show this phenomenon in a static continuous phase.



The heavier dispersed phase begins to drop with an acceleration but soon slows to a constant velocity, u_t.

In practice, this dropping is influenced by other forces caused by continuous operation. In such cases, the continuous phase is not a static phase, but instead is flowing. In a flowing situation, separation is dependent on the arrangement of the vessel; different forces will affect the dropping, which are summarized in the table below.

Regime	Schematics	Analysis	Basic Gravity Separation Formulae
Vertical flow			For removal: $U_V < U_t$ $U_v = f \, . \, u_t$ f = 0.50−0.85
Horizontal Flow			For removal: 1) $\frac{U_t}{H} \geq \frac{U_H}{L} \Rightarrow \frac{h}{L}$ ✓ & 2) $t_{res.} \geq t_{drop.}$ Where: $t_{res.} = \frac{V_c}{Q_c}$ (Vc: volume of vessel occupied by continuous phase) $t_{drop.} = \sqrt{U_t^2 + V_H^2} . \sqrt{H^2 + L^2}$

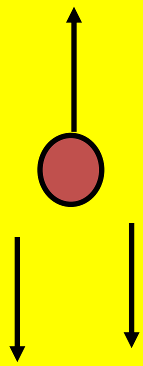
The above equations are for gravity separation. However, a gravity separator shouldn't necessarily be designed solely on the basis of the equations of gravity separation. Other important parameters are involved which affect the design. Sometimes these parameters function as a complementary equation in the design, or are used in the place of portions of the gravity separation equations.

These parameters are mainly hydraulical and economical and comprise:

- Minimizing vessel surface
- Minimizing vessel length of welding line
- Merging the downstream surge vessel with the separator, etc.
- Hydraulically suitable flow inside of separator

How to estimate u_t?

F_A = Archimedes Force = V_d. ρ_c = $\frac{\pi}{6} D^3_d . \rho_c$ Equation 1



W = Weight = $m_d.g = \rho_g.V_d.g = m_d.g = \rho_g. \frac{\pi}{6} D^3_d.g$ Equation 2

F_D = Drag Force = P.A = $(\rho_d H).A = \rho_c . (g. C_D \frac{V_d^2}{2g}) .(\frac{\pi}{4} D_d^2) = \rho_c . C_D . V_d^2 . D_d^2 . \frac{\pi}{8}$ Equation 3

In equilibrium:

$F_g = F_d + W$ Equation 4

Or: $$\frac{\pi}{6} D_d^3 (\rho_c - \rho_d) g = \rho_c . C_D . V_d^2 . D_d^2 . \frac{\pi}{8}$$ Equation 5

Or: $$V_{dt} = \sqrt{\frac{4}{3} . g. D_d \frac{\rho_c - \rho_d}{\rho_c} . \frac{1}{C_D}}$$ Equation 6

Where:

V_{dt} = Terminal Velocity of dispersed phase

D_d = Diameter of dispersed phase

ρ_c = Density of Continuous phase

ρ_d = Density of Dispersed phase

C_D = Drag Coefficient

g = Universal g force

Equation 6 is the principal equation of gravity separation. A problem in Equation 6 is estimating C_D, or drag coefficient. C_D is a function of different parameters including V_t , which is unknown.

One trick to get around the try-and error solution is converting Equation 6 to the below form:

$$V_t = K.\sqrt{\frac{\rho_c - \rho_d}{\rho_c}} \qquad \text{Equation 7}$$

K can be found in different references.

The other trick needs a bit mathematical manipulation. Based on Equation 6:

$$C_D = \frac{4}{3}.g.D_d.\frac{\rho_d - \rho_c}{\rho_c}.\frac{1}{V_{dt}^2}$$

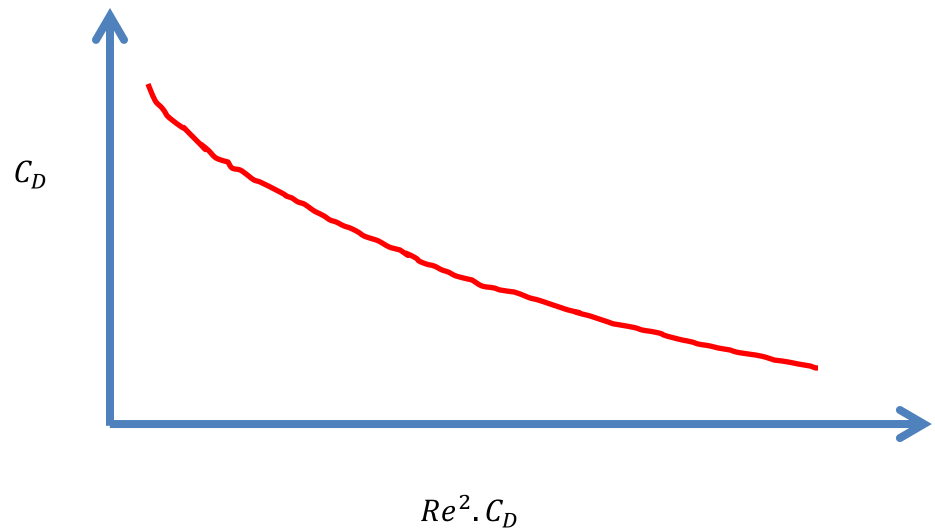
And based on formula for Reynolds number:

$$Re^2 = \frac{D_d^2 V_d^2.\rho_d^2}{\mu_c^2}$$

$Re^2.C_D$ would be:

$$Re^2.C_D = \frac{4}{3}.g.\rho_c.(\rho_d - \rho_c).\frac{D_d^3}{\mu_c^2} \qquad \text{Equation 8}$$

Therefore $Re^2.C_D$ is independent of C_D and $Re^2.C_D$ can be calculated; by using the diagram below (from GPSA), C_D can now be calculated. Thus V_t can be calculated from Equation 6.



$$C_D = -34.8312 + \frac{352.3078}{X^{0.5}} - \frac{1195.63}{X} + \frac{1385.236}{X^{1.5}}$$ Equation 9

Where:

$$X = Ln\,(C_D(Re)^2)$$ Equation 10

u_t calculation limitations:

- In reality, there are some wall effects which decrease U_t.
- The effects of other particles/globules are neglected.
- The above curve is for spherical particles/globules which is not the case for all of them.
- It is difficult to estimate "Dd" to be used in the formula.
- It is common for separating particles/globules to flocculate/coalesce with each other, changing the size of "Dd".

Because of these limitations, the above-mentioned method can only be utilized in "discrete gravity separation".

The different types of gravity separations are:

1. Discrete separation

2. Flocculating/coalescing separation

3. Zone separation

4. Compress (separation)

All separation processes other than discrete separation can only be designed through pilot testing and/or rule of thumbs.

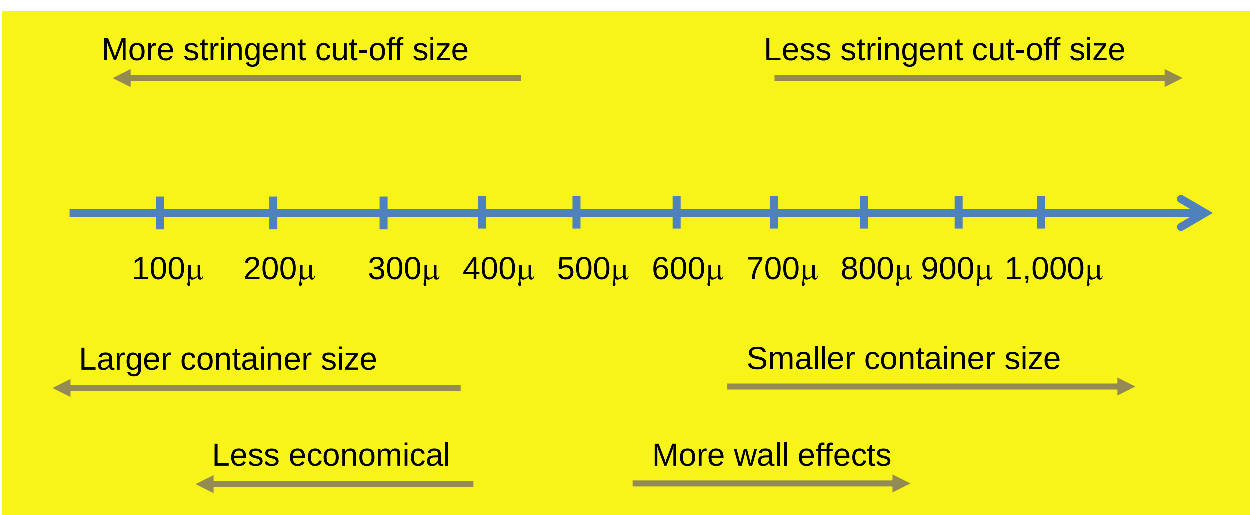
With the exception of very concentrated cases, the last three types of separation usually happen near the interphase of two phases. However, the governing regime is usually discrete separation; the other three types of separation affect the design of the interface zone (sludge or rag layer).

Now the question is which number should be taken as s "D_d", cut-off size?

From theoretical point of view the D_d could be selected in a way to achieve to certain removal efficiency. For example if 90% of particles/globules are bigger than 200 micron, by choosing D_d as 200 micron a removal efficiency of 90% can be attained. A removal efficiency of more than 90-95% is very popular. From the other side; the D_d can be decided based on the downstream equipment. If the downstream equipment can handle e.g. liquid droplet up to 100 micron the D_d can be selected 100 micron irrespective of the required low removal efficiency.

If there is another separator downstream of the separator of interest, the D_d can be relaxed somehow.

Selecting a cut-off size less than 0.2 micron is not allowable because in sizes smaller than that the Brownian movements prevent gravity separation. From the other side, choosing a cut-off size bigger than 1,000 micron is not popular. The below diagram gives an idea about the cut-off sizes.



CONTAINER:

Cylindrical (Horizontal or Vertical), Cubical, Spherical (rare)

Cylindrical: Horizontal vs. Vertical

Definition of vertical vs. horizontal container:

H/D > 1.5-2 ➔ vertical container

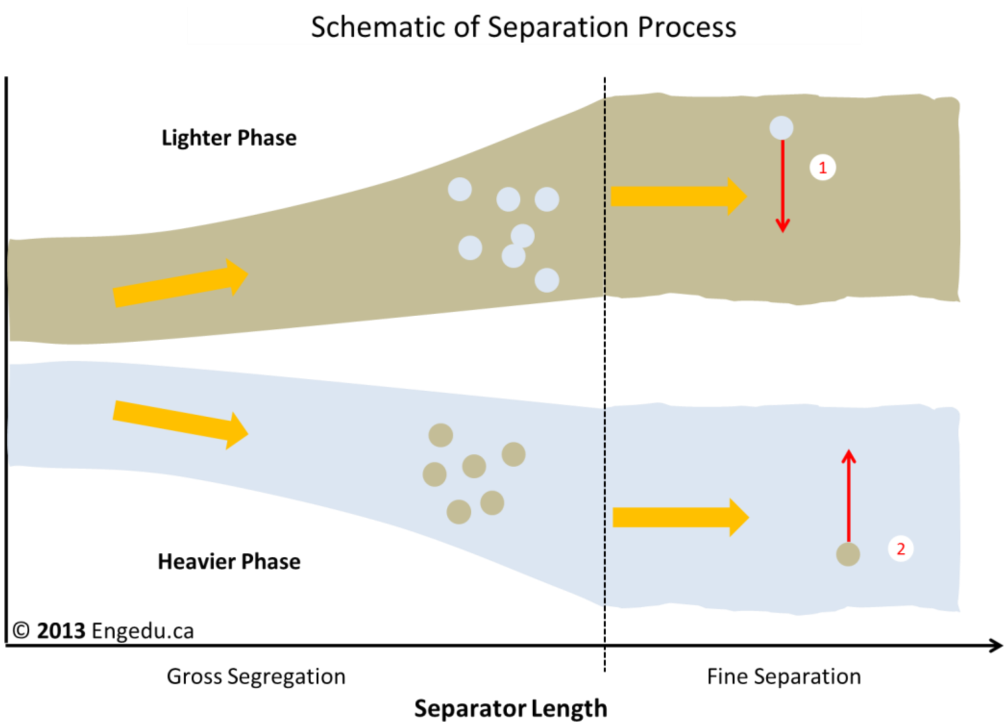
Otherwise, horizontal container

		Dispersed phase		
		Solid	Liquid	Gas/Vapour
Continuous Phase	Solid	NA	NA	NA
	Liquid	Vertical for sludge blanket designs Horizontal for completely mix designs	Vertical: Not Popular unless on off-shore applications Horizontal: Popular	Bubbles in liquid: Very quick removal
	Gas/vapour	Vertical: Popular Horizontal: Sometimes	Vertical: Provides good liquid surge Horizontal: Provides good capacity per cost	NA

SLENDERNESS RATIO & VESSEL DESIGN:

Horizontal: L/D		**Vertical: H/D**	
Low end	**Hi end**	**Low end**	**Hi end**
L/D ≈ 2	L/D ≈ 5−6	H/D ≈ 1.5	H/D ≈ 5
· Start with H/D = 3 for design · For H/D < 2, plug-flow concept deteriorates due to short-circuiting	· Max. is 6 (rarely up to 7 or 8) · 5 is a popular ratio	· Start with H/D = 3 for design · For small scrubbers, start with H/D = 2	· If H/D exceeds 5, use horizontal separator

- If the diameter exceeds 13 ft (up to15 ft), use a tank-type container instead if the pressure is low.
- Try to choose a diameter less than 30 in. In this case, a piece of pipe can be used as the body of the vessel, which is an inexpensive option.
- Round off the diameter to 6 in.
- Round off the length to 3 in.
- When increasing the flow rate, a bigger vessel is needed as separator. Because the cost of a vessel is mainly a function of head diameter, when increasing vessel volume, L/D should be increased to keep the diameter small. This is especially important in high-pressure operations, which need heads (and vessel body) in thick metals.



SEPARATION PROCESS:

As can be seen above, a gravity separation process might initially begin with gross separation (which is usually the case when dealing with gas–liquid or liquid–gas separations, but not liquid–liquid separations), followed by fine separation.

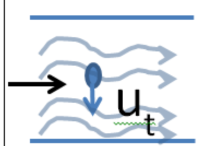
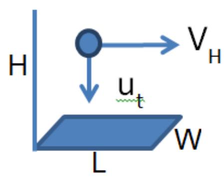
In designing the fine separation portion, two separate designs, in theory, should be considered:

1. Separation of the heavy phase particles from the continuous light phase and;
2. Separation of light phase particles from the continuous heavy phase.

However, in practice, oftentimes the designer has a feeling about the governing design, and only does one calculation.

More information on Horizontal Separator design

In the body of this article the discussion about horizontal separators were limited to the below table to keep the continuity of the article. However, it needs more clarification.

Regime	Schematics	Analysis	Basic Gravity Separation Formulae
Horizontal Flow			For removal: 1) $\frac{U_t}{H} \geq \frac{U_H}{L} \Rightarrow \frac{h}{L}$ ✓ & 2) $t_{res.} \geq t_{drop.}$ Where: $t_{res.} = \frac{V_c}{Q_c}$ (Vc: volume of vessel occupied by continuous phase) $t_{drop.} = \sqrt{U_t^2 + V_H^2}.\sqrt{H^2 + L^2}$

As it can be seen, there are two criteria which should be met to make sure separation happens:

1) $\frac{U_t}{H} \geq \frac{U_H}{L}$ or $\frac{U_t}{U_H} \geq \frac{H}{\mathrm{L}}$

2) $t_{res.} \geq t_{drop.}$ Where:

$t_{res.} = \frac{V_c}{Q_c}$ (Vc: volume of vessel occupied by continuous phase)

$t_{drop.} = \sqrt{U_t^2 + V_H^2}.\sqrt{H^2 + L^2}$

-Different interpretation of rule 1:

Some authors/companies take a conservative approach and use half of the height:

$\frac{0.5H}{\mathrm{L}} \leq \frac{U_t}{U_H}$ More conservative H

And some others take a conservative approach and use half of the terminal velocity:

$\frac{H}{\mathrm{L}} \leq \frac{0.5U_t}{U_H}$ More conservative L

-Different interpretation of rule 2:

-Different approaches on $t_{drop.}$

Instead of using $t_{drop.} = \sqrt{U_t^2 + V_H^2}.\sqrt{H^2 + L^2}$ another parameter, t $_{min.\ drop.}$ can be defined which is the dropping/raising of particle when there is no horizontal flow and then $t_{res.} = F.t_{min.\ drop.}$ F is a factor between one to two and conservatively F=2.

As it was mentioned, t $_{min.\ drop.}$ is defined as the drop time when there is no horizontal element of velocity (V_H=0), or:

t $_{min.\ drop.}$ = $\frac{H}{U_t}$

-Different approaches on $t_{res.}$

$$t_{res.} = \frac{V_c}{Q_c} = \frac{A_V.L}{A_V.V_H} = \frac{L}{V_H}$$

The other approach can be principally based the above simplification (no horizontal flow) and then adjusting the simplification by a factor.

If there is no horizontal flow, the inflow can be considered which comes from the bottom of vessel. Therefore the case would be similar to vertical separator:

$$V_V = \frac{Q_c}{A_H}$$

$U_t = F.V_V$ where F is a factor between one and two.

Therefore:

$$U_t = F.\frac{Q_c}{A_H}$$

The third rule should be checked in designing a horizontal separator is horizontal velocity, V_H. If horizontal velocity of continuous phase (the phase which separation happens in it) exceeds a certain number, the already separated dispersed phase will re-entrain because of turbulence and comes back to the continuous phase.

$V_{H,max.} = 30\ mm/sec$ for liquid as continuous phase

$V_{H,max.} = 3{,}000\ mm/sec$ for gas as continuous phase

Different Zones in a gravity Separator

- *Inlet Zone*
  It needs to be designed to do gross segregation, good flow distribution, and also dampen the momentum of the inlet stream.

- *Separation Zone*
  It needs to be designed to provide calm zone for separation, straightening the streamlines, and also dampen any turbulence.

- *Outlet Zone*
  It needs to be designed to guarantee non-contaminated discharge of each phase.

- *Heavy and/or light phase storage zone*
  It needs to be designed to provide enough room for each phase.

- *Separated phase removing mechanism*
  Sometime it is necessary to implement a mechanism for the purpose of quick and efficient removal of separated phase