

A Primer On Separators and Particle Separation

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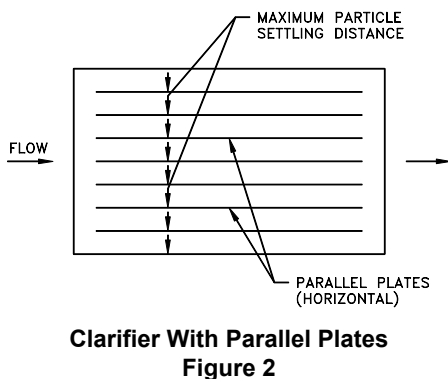
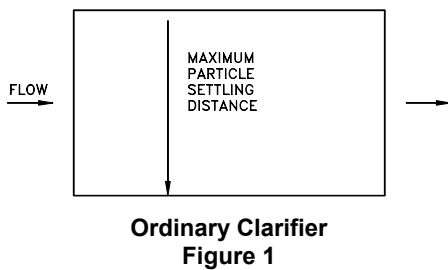
by **C.G. Steiner** as published in *Pollution Equipment News* Volume 18, Number 3, June 1985

Introduction

After a somewhat slow start in this country, plate separators have become preferred equipment for many solids/liquid and liquids/liquid treatment applications. It is apparent that separators are, for the most part, generally replacing traditional clarifiers as the more cost effective process of particle removal from liquid flow streams. Separators, however, do have their limitations. An understanding of the basic principles of particle separation will prevent possible misapplication of this technology.

Background

In 1904, Hazen and his associates theorized that particle removal from a flow stream could be enhanced by inserting parallel plates in an ordinary clarifier (see Figures 1 and 2).



The theory proved to be correct. By inserting the plates, the flow could be increased by a factor directly proportional to the number of plates used without adverse impact on treated water quality. This also proved that particle separation is directly dependent upon the relationship between flow and surface area (called overflow rate) and independent of the residence time and maximum particle settling distance within the clarifier.

Hazen's separator performed rather well for but only a limited time. As solids deposited on the plates, the hydraulic flow path became partially restricted. Eventually, the flow stream would reentrain one separated particles and carry

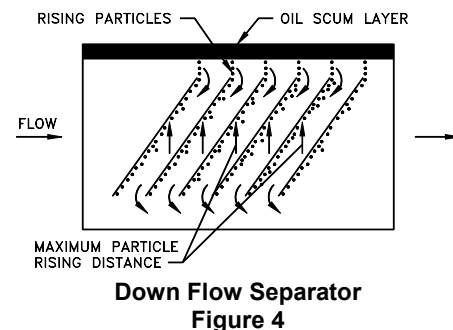
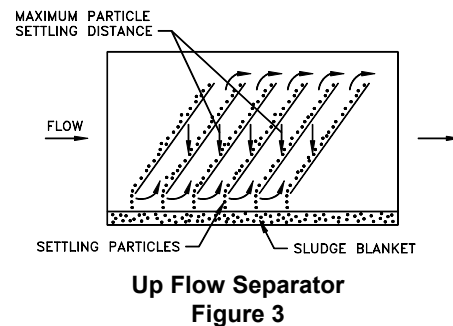
them out with the effluent. The plates would then have to be cleaned of separated solids before resuming service.

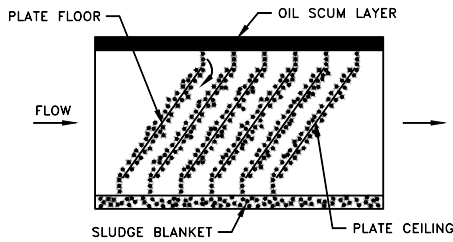
To overcome this cleaning requirement, the plates were tilted, or inclined, at an angle which was in excess of the angle of repose (slide away angle) of the separated particles, thus creating self-cleaning or self-flushing performance (see Figure 3). As heavier than water (a common carrier fluid) particles are falling to the bottom, lighter than water particles are rising to the surface (see Figure 4).

If heavy and light particles are present in the flow stream, both can be removed simultaneously since the solids transport of the heavy particles takes place on the floor of a plate while the scum/oil transport of the light particles takes place on the ceiling of a plate. This is illustrated in Figure 5.

To the extent that "neutral gravity" particles are present, say those within 55 of the specific gravity of the carrier fluid, they pass through a gravity separator and consequently escape removal.

The modern inclined plate separator was thus invented. As distinguished from its horizontal plate predecessor, the total surface area must be calculated as the summation of the cosine of the angle of inclination since the projected surface area, also called effective separation area, is less than the actual plate area.





Cross Flow Separator
Figure 5

General Theory

Gravity clarification permits removal of particles which exhibit densities different from their carrier fluid. Separation is accomplished by detaining the flow stream for a sufficient time to permit particles to separate out.

In water and wastewater treatment practice, particles which rise to the surface of a liquid are said to possess "Rise Rates" while particles which settle to the bottom exhibit "Settling Rates". Both types obey Stoke's Law which establishes the theoretical terminal velocities of the rising and/or settling particles.

Stoke's Law is:

$$V_p = \frac{G}{18\mu} (B - A) D^2$$

where V_p = Rising or settling velocity of discrete particle

G = Gravity constant

A = Density of particle

B = Density of carrier fluid

D = Diameter of discrete particle

μ = Viscosity of carrier fluid

A negative velocity is referred to as a Rise Rate. Oil, scum, and other particles which float to the surface of a liquid are said to possess Rise Rates. A positive velocity is referred to as a Settling Rate. All particles which settle to the bottom of a carrier fluid are said to possess Settling Rates.

An examination of this Law discloses:

- The larger the particle, the faster the rate of separation
- The greater the density difference between the particle and carrier fluid, the faster the rate of separation
- The less viscous the carrier fluid, the faster the rate of separation and vice versa.

Overflow rates. Traditional separation equipment frequently consists of circular and rectangular clarifiers. In a rectangular unit, for example, of

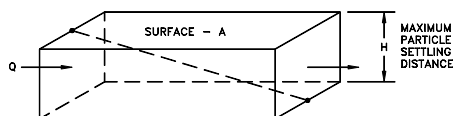


Figure 6

height "H", surface area "A", and hydraulic flow through "Q" (see Figure 6), the residence time " T_r " of the liquid can be determined according to the following equation:

$$T_r = \frac{A \times H}{Q}$$

Now assume that a discrete particle with a positive settling velocity is suspended at the inlet top of the clarifier at point "⊕". The time it takes, designated as " T_p ", for this particle to reach the bottom can be found by dividing the height of

$$T_p = \frac{H}{V_p}$$

the clarifier by the particle settling velocity, or

Particle "⊕" will reach the bottom of the clarifier (and

$$\frac{A \times H}{Q} = \frac{H}{V_p}$$

$$T_r = T_p$$

thereby become separated from its carrier fluid) if the residence time is at least equal to the settling time of the particle. This condition may be expressed as:

In substituting for T_r and T_p , we have

$$V_p = \frac{Q}{A} \quad (\text{Equation 1})$$

which reduces to:

The ratio Q/A is designated as the "overflow rate" of the "surface loading" of the clarifier and is expressed in GPM/sq ft or GPD/sq ft. The overflow rate then, is but a shorthand method of expressing the separation velocity V_p of the particle which the clarifier will remove. For example, an overflow rate of 0.5 GPM/sq ft states that the clarifier or separator will remove all particles with a settling rate of 0.8

$$V_p = \frac{Q}{A}$$

$$= \frac{0.5 \text{ GPM}}{1 \text{ sq ft}}, \text{ which reduces to}$$

$$= 0.06684 \text{ ft/min, or}$$

$$= 0.8 \text{ inches per minute}$$

inches per minute since

Equation 1 above is most significant to separator technology because it proves that neither the height "H" of the clarifier nor its residence time " T_r " influence particle removal. The relationship, rather, between flow and surface area (effective separation area) is controlling.

Reynolds Number. The Reynolds (Re) Number is a mathematical identification of the presence or absence of quiescent settling conditions. When the Re Number is less than 500, particles settle out of a flow stream according to the velocities determined by Stoke's Law. Flow is said to be **Laminar**. Laminar flow conditions permit maximum particle separation to occur. A Re Number above 2000 indicates **turbulent** flow conditions under which settling does not occur. A Re Number between 500 and 2000 indicates flow conditions which are neither laminar nor turbulent. Consequently, some settling does occur, but the efficiency of separation suffers in proportion to the size of the Re Number.

$$\text{Re} = \frac{A \times B \times C}{D}$$

where

A = Hydraulic Diameter in feet

Note: When the fluid flow passageway has a cross sectional shape other than a circle, hydraulic diameter is determined according to the relationship

$$A = \frac{4 \times \text{cross-sectional area}}{\text{wetted perimeter}}$$

B = Density of fluid in lbs/cu ft

C = Linear fluid flow velocity in ft/sec

D = Viscosity of fluid in slugs/ft-sec

The Re Number has a significant impact on the design of separators as is illustrated in the following analysis. If we permit the same flow to pass through identically sized clarifiers, each clarifier is said to be loaded at the same overflow rate (see Figure 7 and 8). However, the performance of each can vary dramatically because of Re Number. If we arbitrarily establish the length as ten times the width, we can then determine the relationship between the relative Re Numbers possessed by each clarifier.

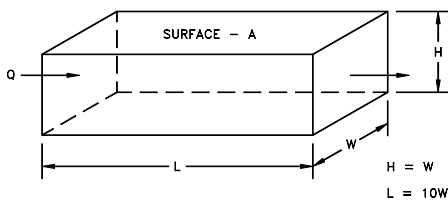


Figure 7

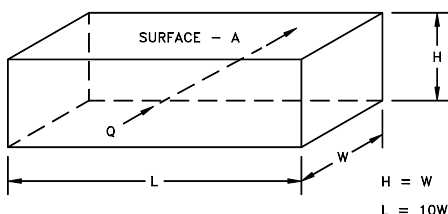


Figure 8

Since the cross-sectional area of the flow path in the Figure 8 clarifier is 1/10 that of Figure 9, its flow velocity is 10 times as fast. If we further eliminate the constant defined by Density ÷ Viscosity, we can then calculate the Re Numbers as follows:

In Figure 7,

$$\begin{aligned} \text{Re} &= \frac{4 \times 1}{4} \times K \times 10 \\ &= 10K \end{aligned}$$

In Figure 8,

$$\begin{aligned} \text{Re} &= \frac{4 \times 10}{22} \times K \times 1 \\ &= 1.82K \end{aligned}$$

In this comparison, the identical flow through identical clarifiers at identical overflow rates can exhibit Re Numbers over five times (5.49) different depending exclusively on the specific flow path utilized.

When these design considerations are applied to plate separators, three interrelated principles are clearly manifested. They are:

1. That the flow path through a separator should be minimized in order to achieve lower Re Numbers and therefore better settling conditions.
2. That the hydraulic diameter should be minimized in order to achieve lower Re Numbers and therefore better settling conditions.
3. That the flow velocity should be minimized in order to achieve lower Re Numbers and therefore better settling conditions.

This says that the optimum separator will incorporate both narrow plate spacing (which decreases the hydraulic diameter) while minimizing flow velocity. This can be achieved by maximizing the cross-sectional area of the flow path, such as that found in cross-flow type separators.

As an example, let's determine the Re Number of a cross-flow separator inclined at 55° from the horizontal with 3/4" plate spacing using 4' wide by 8' long plates at a hydraulic loading of 0.5 GPM/sq ft with water as the carrier fluid @ 68° F.

The hydraulic diameter

$$\begin{aligned} A &= \frac{4 \times \text{cross-sectional area}}{\text{wetted perimeter}} \\ &= \frac{4 \times 8' \times (3/4" \div 12"/ft)}{8 \text{ ft} + 8 \text{ ft}} \\ &= 0.125 \text{ ft} \end{aligned}$$

The water density

$$B = 62.32 \text{ lbs/cu ft @ } 68^\circ \text{ F}$$

In order to determine the fluid velocity through the separator, we must first determine the flow capacity. A single plate contains 32 sq ft of area (8' x 4'). At the stated inclination of 55°, this plate has a projected (effective) surface area of 32 x cosine 55° or 18.35 sq ft. At the stated hydraulic loading of 0.5 GPM/sq ft, the capacity calculates to 9.175 GPM. Since the plates are spaced at 3/4" ÷ 12"/ft) which equals 0.5 sq ft. Dividing the fluid flow per second by the cross-sectional area determines the linear flow velocity, or

$$C = \frac{9.175 \text{ GPM}}{60 \text{ sec/ min} \times 7.481 \text{ gal / ft}^3 \times 0.5^2}$$

$$= 0.0409 \text{ ft/sec}$$

The fluid viscosity

$$D = 0.00067533 \text{ slugs/ft-sec @ } 68^\circ \text{ F}$$

The Re Number may now be calculated as:

$$\text{Re} = \frac{ABC}{D}$$

$$\text{Re} = \frac{0.125 \times 62.32 \times 0.0409}{0.00067533}$$

$$= 472$$

As a further example, let's determine the Re Number of a counter current, or co-current flow separator inclined at 55° from the horizontal with 2" plate spacing using 4' wide by 8' long plates at a hydraulic loading of 0.5 GPM/sq ft

$$A = \frac{4 \times \text{cross - sectional area}}{\text{wetted perimeter}}$$

with water as the carrier fluid @ 68° F.

$$= \frac{4 \times 4' \times (2" \div 12"/ft)}{4 \text{ ft} + 4 \text{ ft}}$$

$$= 0.333 \text{ ft}$$

The water density

$$B = 62.32 \text{ lbs/cu ft @ } 68^\circ \text{ F}$$

The flow capacity again calculates to 9.175 GPM. Since these plates are spaced at 2", the flow passageway cross-sectional area may be determined by multiplying the plate width by the spacing or 4' x (2" ÷ 12"/ft) which equals 0.67 sq ft. Dividing the fluid flow per second by the cross-sectional area determines the linear flow velocity, or

$$C = \frac{9.175 \text{ GPM}}{60 \text{ sec/ min} \times 7.481 \text{ gal / ft}^3 \times 0.67 \text{ ft}^2} = 0.0305 \text{ ft/sec}$$

The fluid viscosity

$$D = 0.00067533 \text{ slugs/ft-sec @ } 68^\circ \text{ F}$$

The Re Number may now be calculated as:

$$\text{Re} = \frac{A \times B \times C}{D}$$

$$\text{Re} = \frac{0333 \times 62.32 \times 0.0305}{0.00067533}$$

$$= 937$$

As in Figures 7 and 8, two identically sized separators operating at identical overflow rates have significantly different Re Numbers. The former operates within laminar flow conditions whereas the latter operates under hindered settling conditions.

Internal Hydraulics. The flow passageway has a direct impact on the Re Number and therefore on laminar flow conditions. At a specific hydraulic loading rate, the shortest flow path through the separator will always result in the least flow velocity and therefore the lowest possible Re Number. To achieve a short flow path requires a large entry plane into the separator along with appropriate hydraulic distribution and collection is under utilization of plate surface area. Likewise, separator designs with small entry planes possess inherently higher Re Numbers and thus must be rated at reduced hydraulic loadings to achieve laminar flow conditions.

If the path of the particle to be separated (and thus in transport along the plate) is opposite to, or countercurrent to, the path of the carrier fluid, some of the particles with lesser settling/rise rates will be swept into the fluid flow. This is referred to as particle reentrainment. Particle reentrainment always degrades the quality of the effluent as well as the efficiency of performance. Particle reentrainment can be eliminated by:

1. Directing the paths of the separated particles and the fluid flow so that the respective paths are 90° from each other. This can only be achieved in a cross-flow type separator.
2. Causing the smaller particles (those possessing less settling/rise rates) to coalesce together thereby agglomerating and forming larger particles. Particle settling/rise rates are proportional to the square of their diameter according to Stoke's Law previously discussed. Particle coalescence therefore enhances separator performance while minimizing particle reentrainment.

Particle Coalescence. Particle coalescence is important to enhance because the rate of separation (rising or settling) is directly proportional to the square of its diameter. By encouraging particles to join together to form larger and larger particles, the efficiency of separation is increased accordingly.

As separated particles migrate along a flat plate, some particle agglomeration takes place due to the collision between particles exhibiting different migration (solids transport) rates. This agglomeration takes place in the dimension or direction of particle migration. As separated particles migrate along a corrugated plate, by comparison, they slide to the trough of the corrugations. This phenomenon

of concentration is called coalescence. As these coalesced particles continue migration, they also agglomerate due to collisions between particles exhibiting different migration rates. However, in a corrugated plate separator, particle agglomeration is actually achieved in two dimensions, whereas in a flat plate separator, particle agglomeration is achieved in a single dimension. Figure 9 illustrates particle coalescence and simultaneous separation of rising and settling particles.

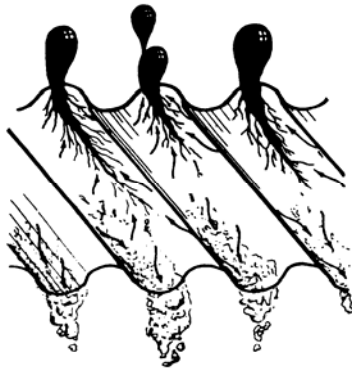
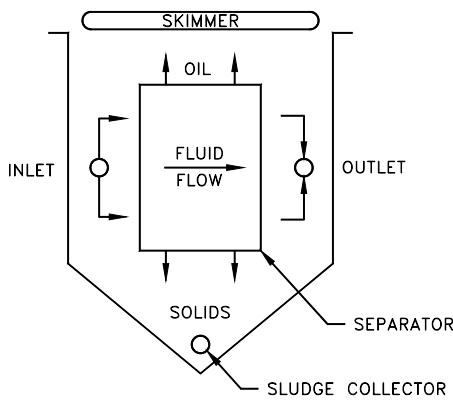


Figure 9

Application Engineering Considerations

Separators are used to separate settling particles, rising particles, and also neutral gravity particles. Separators which separate settling particles are called solids/liquid separators or simply solids separators. Separators which separate rising particles are called liquid/liquids separators or simply oil/water separators (their most frequent application). In a cross flow type separator, both kinds of particles may be simultaneously removed (see Figure 10).



Solids Separator & Oil/Water Separator

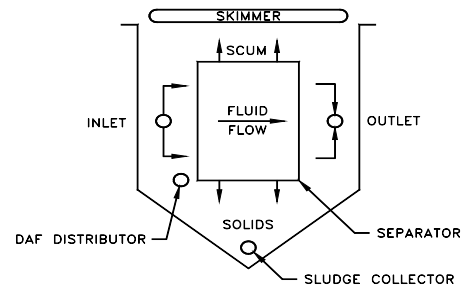
Figure 10

Particles which exhibit rapid rise and/or settling rates are easy and inexpensive to remove. Particles which do not rise or settle are said to be neutral gravity particles. Particles exhibit neutral gravity when their specific gravity is close to the specific gravity of the carrier fluid. Particles may also exhibit neutral gravity when their size is extremely small, regardless of their specific gravity. For example, very pure mercury (99.999%), which has a specific

gravity of 13.6 will form a somewhat stable mechanical emulsion with pure water for up to two hours. As a mechanically emulsified particle of about 10 microns in size, it will not readily separate in spite of its great relative weight in water! To separate neutral gravity particles requires further process treatment.

In the case where neutral gravity is caused by the specific gravity of the particle itself, two treatment options are available. This neutral gravity particle may be small or large. If the particles are large they may be removed in a DAF (Dissolved Air Flotation) separator as is illustrated in Figure 11.

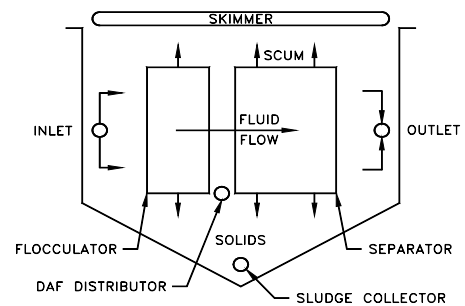
In a DAF separator, air saturated recycled water under elevated pressure is distributed in front of a separator. Excess air “boils” out of the water once the pressure is reduced to gravity conditions. These micron sized air bubbles attach to the large neutral gravity particles and float them to the top of the separator.



DAF Separator

Figure 11

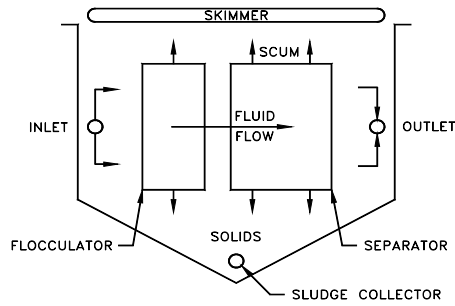
If the neutral gravity particles are small, chemical pretreatment followed by flocculation is necessary to agglomerate the particles. Once agglomerated, they may be removed in a Flocculator/DAF separator as is illustrated in Figure 12.



Combination Flocculator DAF Separator

Figure 12

In those cases where neutral gravity is caused by the small size of the particle itself, chemical pretreatment followed by flocculation is necessary to agglomerate the particles. Once agglomerated, they will exhibit sufficient separation velocities and may be removed in a Flocculator/Separator as is shown in Figure 13.



**Combination
Flocculator Separator**

Figure 13

If the flow stream contains settling particles and neutral gravity particles, a first stage separator is necessary to remove the neutral gravity particles. Any attempt to short circuit this two-stage separation process with a single stage DAF separator could result

in the heavy particles becoming neutral gravity particles due to the attached air. A Separator/DAF Separator is required as is illustrated in Figure 14.

In the case of a flow stream containing large quantities of free oil along with significant quantities of chemically emulsified oil, a three stage treatment system consisting of a separator to remove the free oil, followed by chemical feed and flocculation in a second stage, and finally DAF separation in a third stage to remove the emulsified oil will be necessary. This method of treatment is required since emulsified oil particles are both small and exhibit neutral gravity and furthermore cannot be flocculated satisfactorily in the presence of large quantities of free oil.

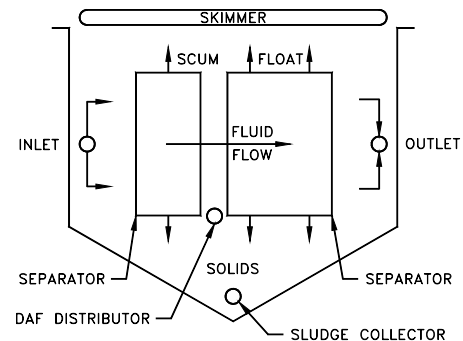
Conclusions

The effective separation of all types of particles can be achieved rather easily if the foregoing treatment principles are utilized. In order to effectively apply these particle separation techniques, one must identify with precision:

1. The particles which are present, quantities, and separation rates at intended temperatures of operation, and
2. The particles which require removal to satisfy treatment objectives.

Extensive laboratory testing may be required to identify separation rates, to establish chemical dosage and flocculation gradients through jar tests, to determine particle sizes and specific gravities, and to determine probable separation efficiencies. In some cases, pilot plant testing may be desirable on more complex separation problems.

The separator design considerations of overflow rate, operating temperature, specific gravities, settling/rise rates, and carrier fluid viscosities must be addressed before separator sizing can be established



**Combination Separator
DAF Separator**

Figure 14

To specify a 1000 gpm oil/water separator for, example, without further qualifying criteria is an insufficient specification. In addition to the flow rate, the designer must know:

1. Design temperature of operation,
2. Specific gravity differential between particles to be removed and the carrier fluid, and
3. The diameter of the minimum sized oil particle to be removed.

The same qualifying criteria also apply to solids separators.

There are now about 20 suppliers of separation equipment vying for this rapidly increasing market. The principles of particle separation apply equally to all these suppliers. By acquiring a fuller understanding of your particular separation application, you also acquire an enhanced ability to evaluate your process equipment requirements.

