



PRODUCED WATER SOCIETY

Gas Flotation Technology

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The term “Gas Flotation” is sometimes used as if it is one technology.

It is not.

There is a wide range of flotation technologies available today. Some have 95 % separation efficiency, but are large and heavy, others have 50 % separation efficiency but are compact. Others have 30 % separation efficiency but are inexpensive.

Our goal in this paper is to provide some guidance in selecting the most appropriate flotation technology for a given application.

The following table gives the range of variables for commercially available flotation equipment on the market

Parameter	Minimum	Maximum
Gas/Water Ratio	0.12	8.5
Residence time (minutes)	0.5	4
Height/Width ratio (m high/m diameter)	1	4
Bubble size (microns)	30	1,200
Reject percentage	0.5	7

No particular machine (model of flotation) has all minimum or maximum values.

This slide illustrates the differences that can be found in the marketplace from one flotation technology to another.

In the E&P industry, there are several factors that drive the selection of a particular flotation technology. These include:

- total cost (including weight, space and chemical)
 - schedule
 - operability
 - after-sales service
 - separation efficiency

Among these factors, separation efficiency is often the most difficult to predict.

We will discuss the fundamentals of flotation, and use theory combined with field observation to explain why some flotation designs provide greater separation efficiency than others.

To begin the discussion, we need to have a common understanding of how flotation works.

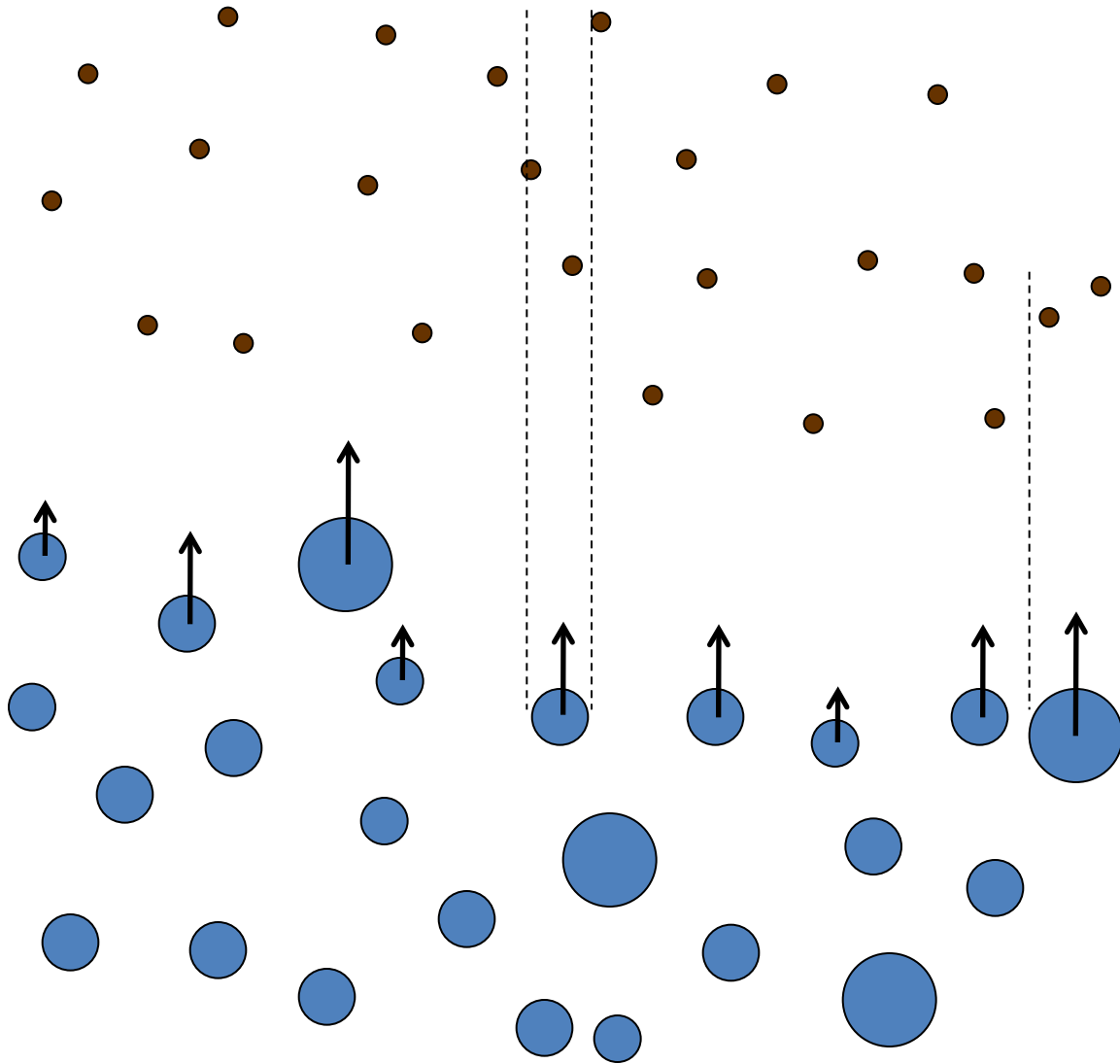
Bubbles rise and crash into oil drops.

Some of the oil drops are captured by the bubbles.

The bubbles continue to rise to the water surface where they join other bubbles to make a foam.

The foam continuously collapses allowing pools of oil to form.

The oil is swept off, scraped off, pushed off or allowed to fall off the surface of the water into a separate trough.



Gas bubbles rise rapidly and collide with the oil drops

The collision frequency depends on the concentration of oil drops, the concentration of gas bubbles, and on the projected areas of the oil drops and the gas bubbles.

When an oil drop and a bubble collide, the oil drop doesn't necessarily get captured by the bubble.

The oil drop can slide off the surface of the bubble, or be carried around the bubble by the hydrodynamics of the flow.

Whether or not an oil drop gets captured depends on the complex fluid dynamics around the rising bubble, and on the surface chemistry between the bubble and drop.

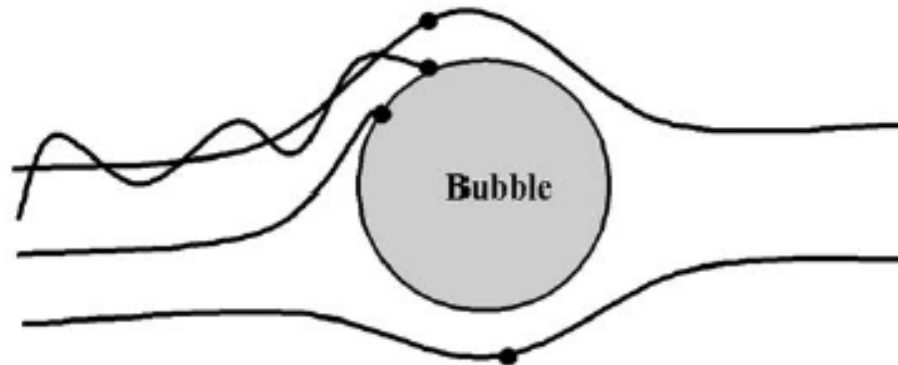


Fig. 1. Schematic of typical particle paths around a bubble caused by relative motion between the bubble and surrounding slurry. The tendency of particles to follow streamlines, as illustrated, reduces the collision frequency below the straight path interception frequency. The mechanism by which small-eddy turbulence can increase collision frequency is illustrated by the upper particle path.

Question: what do you think is the fraction of collisions that result in capture of the oil drop?

Answer:

(without flocculating agents or deoiling chemicals)

When large bubbles are used (700 micron) capture efficiency is roughly 1 in 10,000.

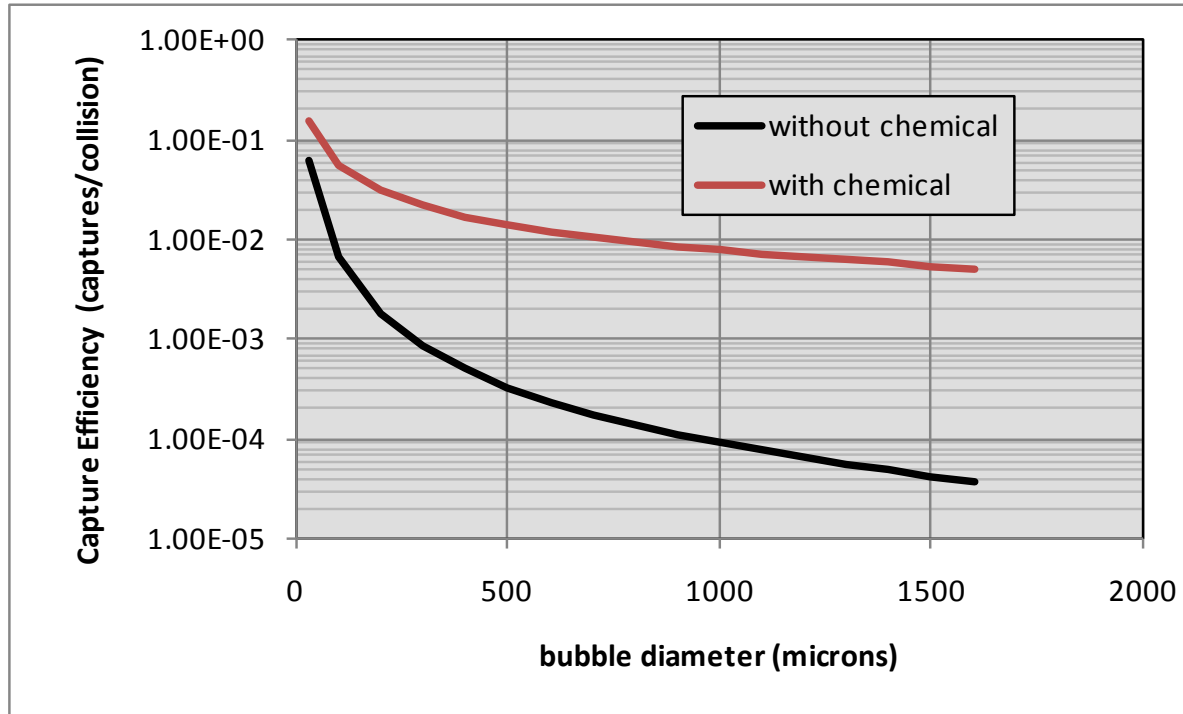
When small bubbles are used (30 micron) capture efficiency is roughly 1 in 100.

Q: why are these values so low?

A: because gas bubbles rise fast (large density difference with water) and the small oil drops tend to follow the currents which carry them around the bubbles. The oil drops follow the “streamlines” around the gas bubbles. The larger the bubble, the faster it rises and the fewer oil drops it will collect.

Ref.: Ramirez & Davis, Separation Science and Technology, v. 36, p. 1-15 (2001)

... but with chemical, capture efficiency improves significantly, particularly for large bubbles:



The use of chemical significantly improves capture efficiency.
This is why chemical is so important for flotation.

With chemical, capture efficiency is roughly 1/100 for large bubbles.
It is 1/10 for small bubbles.

An important point to notice here:
Without chemical, capture efficiency is proportional to $1/d^2$
With chemical, capture efficiency is proportional to $1/d$
We will return to this later.

Other Factors:

Besides chemical, turbulence improves the capture efficiency.

Turbulence makes the trajectory of the oil drop and gas bubble more random and hence the oil drops deviate from the hydrodynamic streamlines.

Large bubbles create more turbulence.

Rotating paddles also create turbulence.

Swirl motion increases the retention time.

Internal baffles force oil and gas bubbles to collide in a small cross sectional area.

Coalescing elements provide surface area for coalescence.

Besides capture efficiency, the number of collisions is important as well.

But how important?

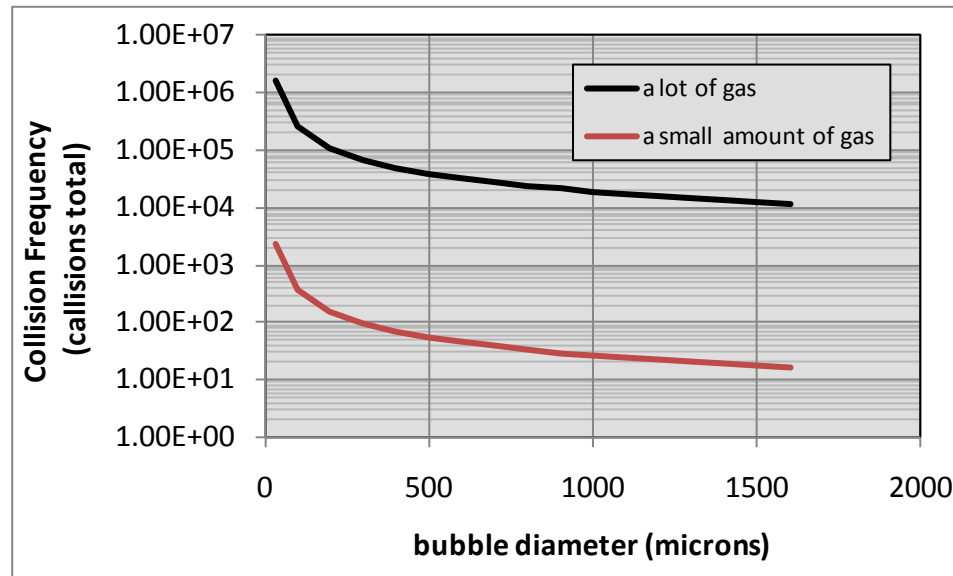
The more gas that is used, of course, the more bubbles are generated. The more bubbles, the more collisions there are between bubbles and oil drops.

The more collisions there are, the more oil drops that are captured.

But, the more gas that is used, the more expensive (generally).

Can we quantify this (as we did for capture efficiency)?

Collision frequency as a function of the amount of gas that is used and the bubble size:



Collision frequencies are very large numbers compared to capture efficiencies.

So all machines overcome poor capture efficiency to greater and lesser extent by adding chemical and by having a lot of bubbles which dramatically increases the collision frequency.

The greater the amount of gas, the greater the number of bubbles, the greater the number of bubbles, the greater the collision frequency.

The kinetic theory of flotation allows the calculation of oil capture

Physically, gas bubbles and oil drops rise at different rates according to Stokes law: V_{12}

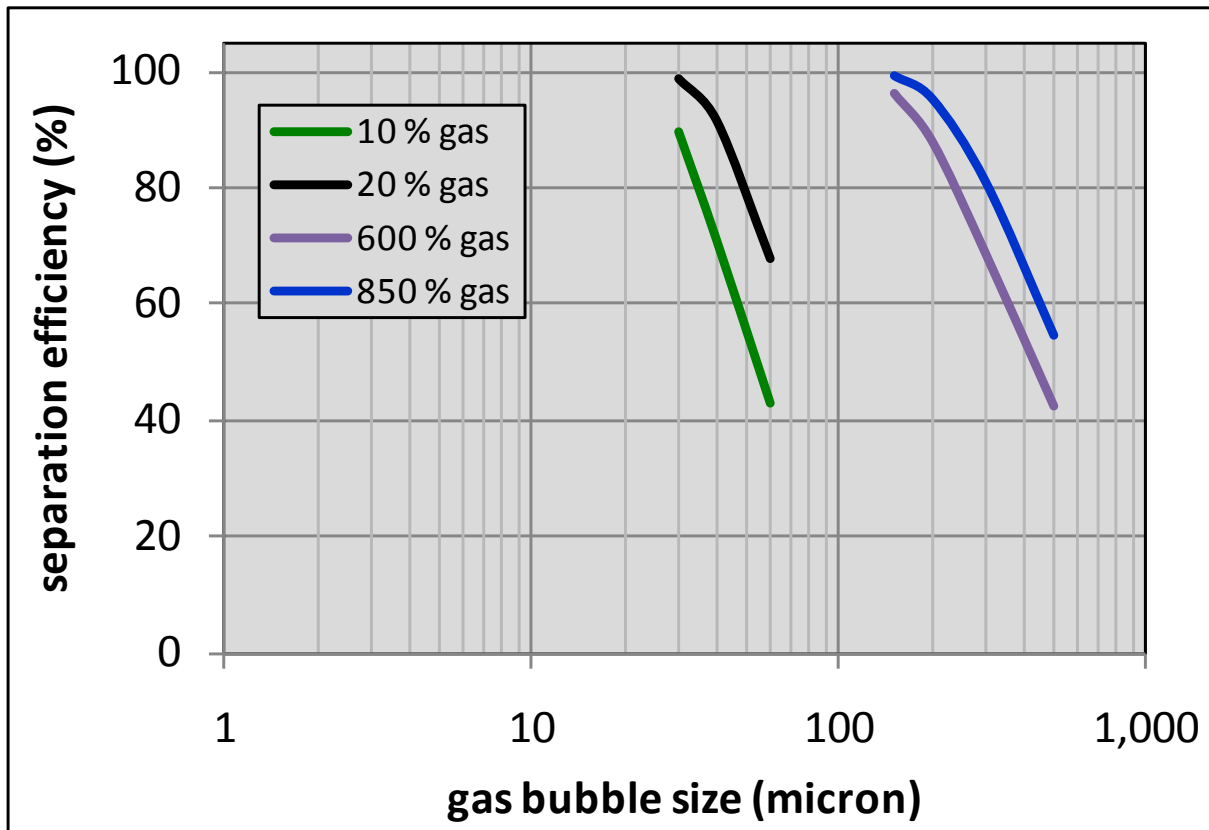
The probability of collision is equal the cross sectional area of bubble and drop: $\pi(a_1+a_2)^2$, and the concentration of oil drops (n_1) and bubbles (n_2)

The capture efficiency accounts for the fraction of collisions that result in capture of an oil drop: E_{12}

$$\frac{dn_2}{dt} = -n_1 n_2 \pi (a_1 + a_2)^2 V_{12} E_{12}$$

where:

- n_1 number density of gas bubbles (number of bubbles per unit volume)
- n_2 number density of oil drops (number of drops per unit volume)
- a_1 radius of gas bubbles
- a_2 radius of oil drops
- V_{12} relative velocity of bubbles and drops (Stokes Law)
- E_{12} bubble-droplet capture efficiency



The model allows a theoretical calculation of oil removal efficiency as a function of typical gas flotation variables such as:

- Gas bubble diameter
- Gas/water ratio (sfc gas/ft³ water)
- Oil drop diameter

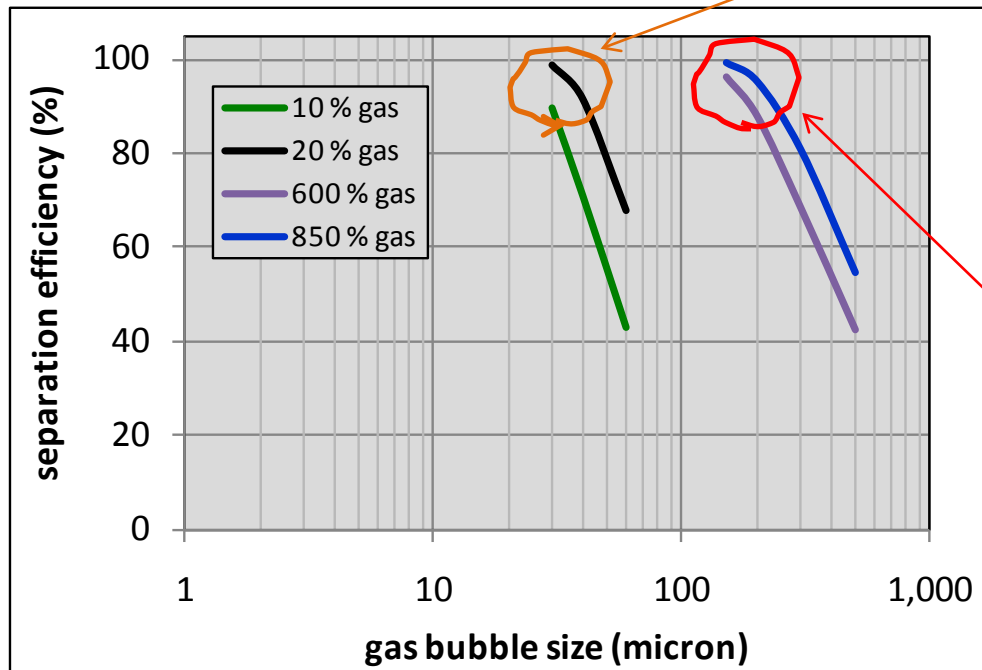
Shown in the figure are efficiencies for two types of flotation machines:

- Small bubbles / low gas rate
- Large bubbles / high gas rate

Oil drop size: 20 microns; 1 minute residence time.

With some equipment you get large bubbles and lots of gas, and with other equipment, you get small bubbles but not much gas.

Unfortunately, there is no machine that gives small bubbles and a lot of gas. The reason for this, is partly related to mechanical configuration and to the cost of generating gas bubbles.



The small bubble machines deliver much less gas and so bubble size and gas rate become very important – note the gap in performance between 10 % gas and 20 % gas. These machines are not so forgiving.

The large bubble, high gas volume machines, achieve high efficiency over a comfortable range of gas rates and bubble sizes.

A summary of what we have discussed so far:

Collision Frequency: Collision frequency increases as gas flow rate increases because more gas means more bubbles.

Collision frequency increases as bubble size decreases because the number of bubbles increases as the bubble size decreases,

Capture Efficiency: Capture efficiency increases as the bubble size decreases because larger bubbles move too fast to capture the slow moving oil drops. But this effect is less pronounced when chemical is added.

One other factor that intuitively seems important is the shape of the flotation machine. By “shape” we mean, how tall and wide is the unit.

The shape of the active zone of most flotation devices is roughly a cylinder. Even a square Wemco really has a cylindrical active zone. Some machines, like a Unicel, have an inner pipe for oil/gas contact. We refer to cylinder as the contact cylinder.

The contact cylinder is the “reaction zone.” The longer it takes a bubble to rise through the contact zone, the more oil drops it will encounter and the more collisions it will have on its way to the top of the water. This concept is known as “sweep” (ref: T. Frankiewicz, others). Sweep goes up as bubble size goes down.

Similarly, the longer the water stays in the contact cylinder, the more bubbles it will encounter. This is known as retention time. The longer the retention time, the larger the machine.

The time that a bubble stays in the contact zone, as it rises, is a function of the height of the contact cylinder, the water flow rate, the gas flow rate, and the rise velocity of the bubble (diameter squared).

The time that the water spends in the contact cylinder is given by:

$$t_c = V_c / Q_w$$

t_c = contact time (time that oily water and bubbles are in contact (minutes))

V_c = volume of the contact cell (m³)

Q_w = volumetric flow rate of water (m³/minute)

$$\text{number of bubbles per unit area per unit time} \cong Q_g / A_c d_g^3$$

d_g = diameter of gas bubble (micron)

Q_g = volumetric flow rate of gas (m³/minute)

A_c = cross sectional area of the contact cell (m²)

$$\text{cross sectional area of bubbles} \cong d_g^2$$

Combining these terms gives the Flux Factor: $N_F = (H_c / d)(Q_g / Q_w)$

H_c = height of the contact cell

The Flux Factor is a dimensionless parameter which characterizes the mechanical design of a flotation unit.

In the material below, the Flux Factor is correlated with field observations of the separation efficiency.

This correlation will help us decide:

- Should we buy a machine with long residence time, which may cost more? Or can we buy a less expensive machine that has a tall and narrow contact cylinder?
- Is it worthwhile to invest in a machine that can generate a lot of gas? We know this is good, but again it is also more expensive. Also, it is more dependent on chemical selection and dosage.
- Should we invest in a machine with small bubbles? They seem to do a better job capturing small oil drops, but they are limited in the amount of gas and hence in the number of collisions.

The flux factor is defined as:

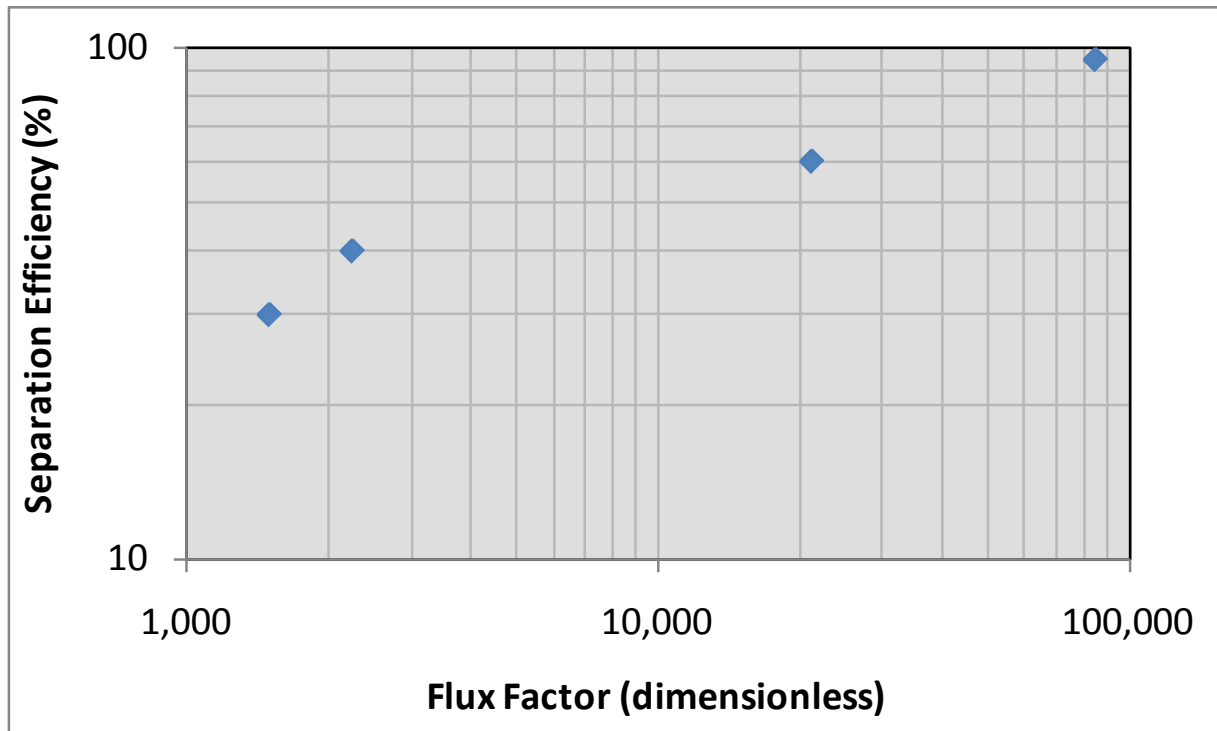
$$(H/d) * (Q_g/Q_w)$$

H: height of machine

d: gas bubble diameter

Q_g / Q_w : gas / water ratio

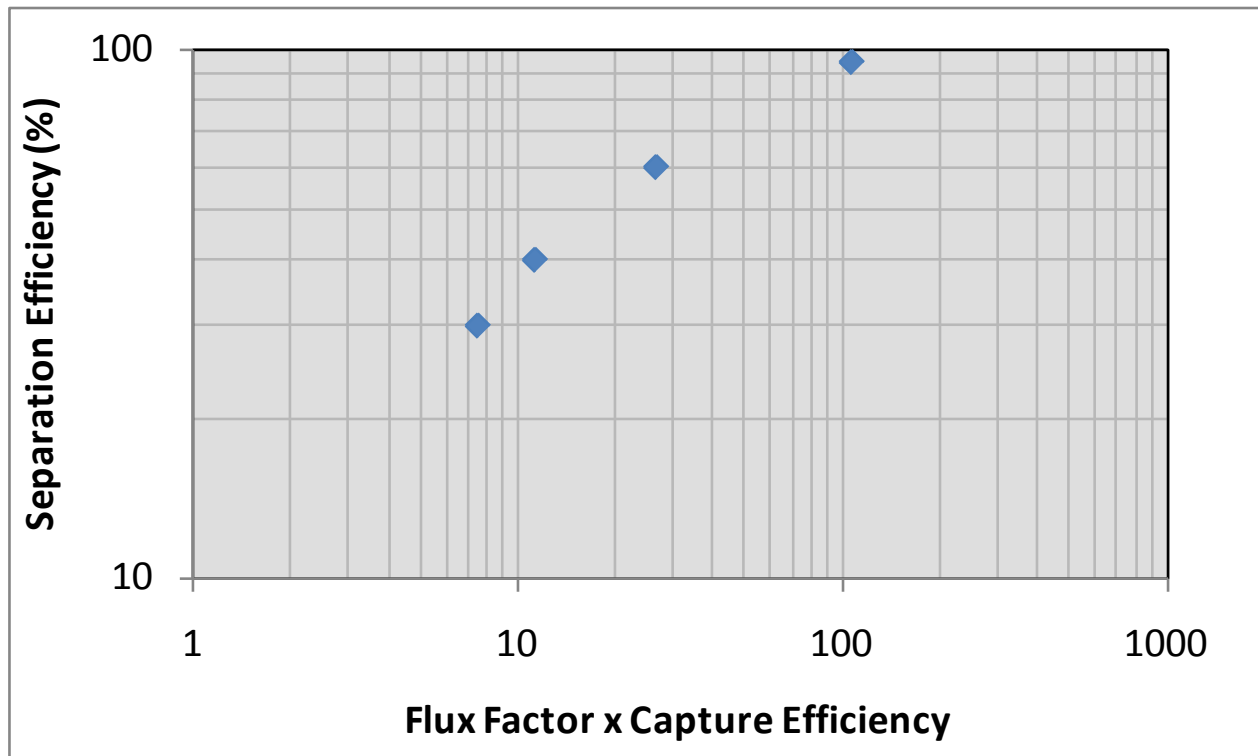
Field observations of separation efficiency:



The Flux Factor gives a measure of the effectiveness of the design of a flotation machine but it does not account for capture efficiency.

Capture efficiency can be included in the correlation. Here we use $1/d$ (gas bubble diameter).

$$(H/d) * (Q_g/Q_w) \times E_{12}$$



A smooth correlation exists between separation efficiency and Flux Factor times Capture Efficiency

This gives a way to estimate the separation efficiency of a particular flotation design

The discussion presented here is useful for judging the design of one flotation unit versus another.

A good correlation was found between separation efficiency and Flux Factor times Capture Efficiency.

In the data shown, chemical was used.

Other factors are also important such as oil drop size, presence of coalescing elements or internal baffles, etc. These are not accounted for.

We do not wish to show which vendors give which results – call us to discuss.

... except to say that the horizontal, multi-stage IGF gives the highest Flux Factor and gives the highest separation efficiency, despite having large gas bubble diameters. The large volume of gas and the multistage effect (J. Chen et al.) overcomes the detrimental effects of large bubbles.

But so far, the discussion has not given us a practical tool to select which machine is right for the job.

To do that:

we provide a dimensionless number. This dimensionless number is based on the concepts that we just talked about (e.g. bubble size, collision rate, capture efficiency, etc), but also practical considerations such as height, diameter, residence time, etc..

The best flotation technology, for a given application, is the one that reduces total cost of ownership while complying with environmental legislation.

Your total cost of ownership may be driven by capital availability, lack of space, by high cost of added weight, schedule constraints, or by a produced water that is difficult to treat.

You can actually pick the right machine to suit your needs.

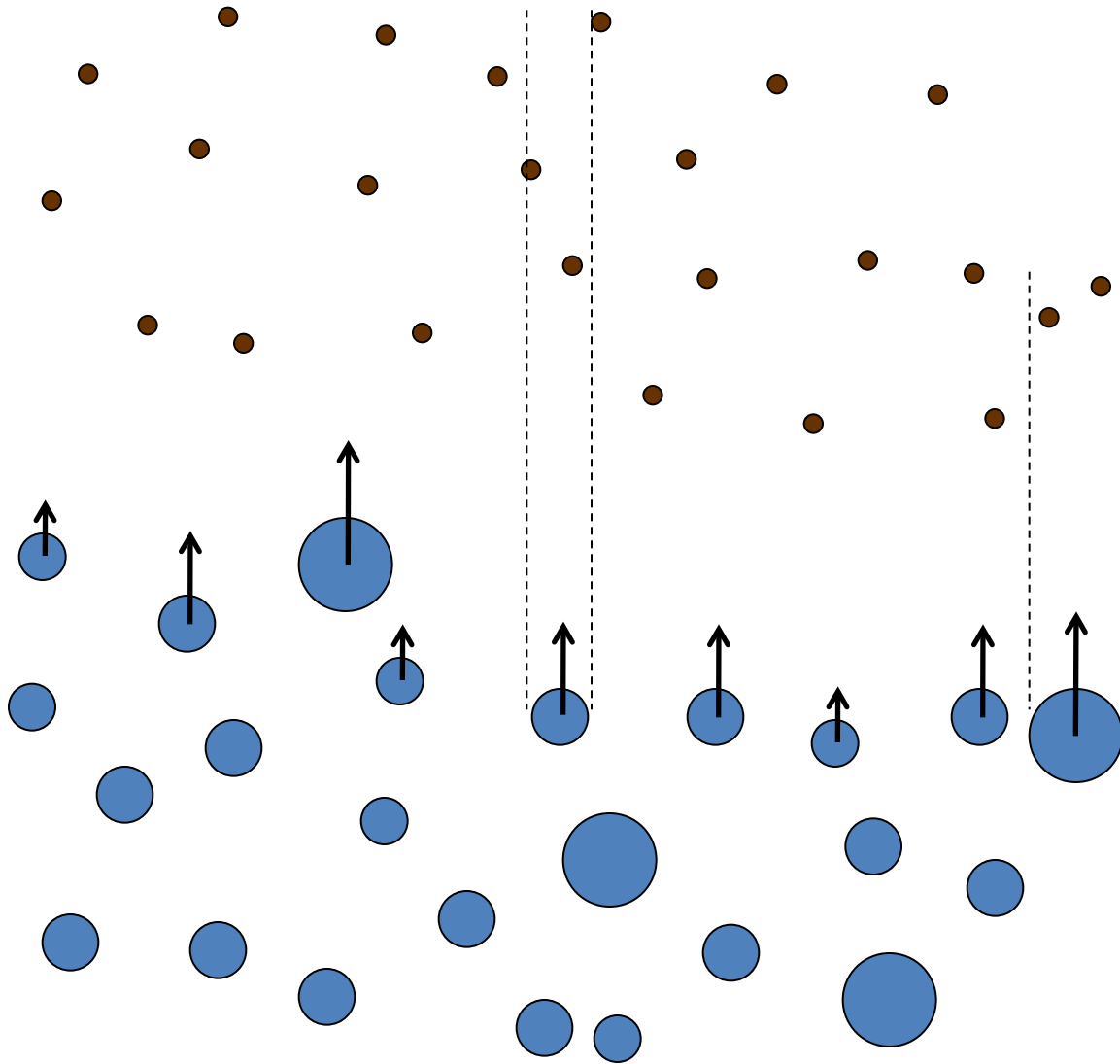
Questions

Up to this point, the discussion has been theoretical.

It has helped us understand the mechanism of oil removal using flotation, and has given us a feel for the order of magnitude of certain concepts such as:

- collision frequency,
- capture efficiency,
- and sweep (which is related to the amount of time that bubbles stay in the contact cylinder).

But so far, the discussion has not given us a practical tool to select which machine is right for the job.



Gas bubbles rise rapidly and collide with the oil drops

The collision frequency depends on the concentration of oil drops and gas bubbles, and on their respective projected areas.

Very few collisions lead to capture of oil drops by gas bubbles. This is known as the “capture efficiency.” It is roughly 1/1000.

The capture efficiency depends on the surface chemistry of the oil and gas. It is strongly affected by chemical additives such as flocculating agents, coalescing agents, and other surface active chemicals.