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Outline:

Broad overview of flotation equipment

Mechanism of oil drop capture by gas bubbles

Equipment design considerations
Features of particular brands and models of flotation equipment

Modeling performance for troubleshooting and design

Representative performance data discussed with respect to the mechanisms and design considerations.
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.

Depending on the application, there is likely at least one or more models of flotation technology that is most suitable.

- 95% separation efficiency & large and heavy
- 50% separation efficiency & compact
- 40% separation efficiency & both compact and inexpensive.

The goal of this paper is to provide some guidance in selecting the most appropriate flotation technology for a given application.
Wemco Depurator – Mechanical Induced Flotation

Petreco – Hydraulic Induced Flotation
Internal (submerged) Eductor

Natco ISF – Mechanical Induced Flotation
Pressure Vessel Design

Petreco Unicel – 2 – Stage Vertical
Bottom Feed Co-Current
Hydraulic Induced Flotation
External Eductor
The following table gives the range of variables for commercially available flotation equipment on the market:

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

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.

The fundamentals of flotation will be discussed. Theory will be combined with field data to explain why some flotation designs provide greater separation efficiency than others.
Flotation within an oil/gas/water Separation System:

- production separators vessels or skim tanks
- hydrocyclone flotation unit
- horizontal multi-stage mechanically induced flotation
- vertical single-stage hydraulically induced gas flotation
Integration of Equipment into a Water Treating System:

Flotation is a secondary process. It is always located downstream of primary separators. If hydrocyclones are present in the system, flotation is always located downstream of the hydrocyclones.

The reason for this is two-fold:

1) Flotation is typically capable of separating smaller drops than primary separation and hydrocyclones.

2) The reject flow rate and oil concentration must be accounted for in the overall process flow. This means that the separators must be large enough to handle the flotation reject flow rate.
Ultimately, the reject must be recycled in order to capture the oil contained in the oily water recycle. Here, flotation reject is routed to a Slop Tank for chemical treatment and settling time. This reduces recycled chemical, and provides additional oil/water separation before recycle into the rest of the system.
To begin the discussion of different flotation machines, 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 an oily foam.

At the top of the oily water, the foam continuously collapses allowing pools of oil to form.

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

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.
In addition to collision frequency, capture efficiency is important.

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

Answer:

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.

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: $\pi(d_o + d_g)^2$, and the concentration of oil drops ($n_o$) and gas bubbles ($n_g$).

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

$$\frac{d \ln(n_o)}{dt} = -\pi n_b (d_o + d_b)^2 V_{12} E_{12}$$

$$(Q_g / Q_w)(\pi a_b^2 / 4) / (\pi a_b^3 / 6) = (Q_g / Q_w)(3 / 2a_b)$$

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 size of the oil drop shown here is roughly 10 times larger than realistic.

This sequence will be discussed later in relation to the chemistry of the oil/water/gas interaction. For now, it is noted that there are several steps in order for a successful capture of an oil drop.
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 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.
Some equipment provides large bubbles and lots of gas, and other equipment provides 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. Generating small bubbles is expensive.

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.
Design Choice – amount of gas and bubble size:

![Graph showing the relationship between gas/water ratio (GWR) and gas bubble diameter (micron) for different collision frequencies. The graph includes data points for flotation machines and lines for high, medium, and low collision frequencies.]
Summary of Flotation Mechanism:

**Collision Frequency:**
- Gas to Water Ratio: more gas = more bubbles.
- Bubble size: small bubbles = more bubbles.

**Capture Efficiency:**
- Bubble size: small bubbles = slower = more time for coalescence and oil spreading on the gas bubble.

Good oil/water separation = small bubbles, high gas to water ratio. However these are two items are the main cost drivers.
This concludes the sections on
Broad overview of flotation equipment
Mechanisms of oil drop capture by gas bubbles

The next section is about chemical treating

After that:
Design of Equipment
Models available
Performance Data
Modeling

Are there any questions?
Various flocculant reactions:

- **Initial adsorption**
  - Polymer + Colloidal particle → Destabilized particles → Floc

- **Secondary adsorption**
  - GOOD → Restabilized particle

- **Initial adsorption (excess polymer dosage)**
  - Excess polymers + Colloidal particle → Stable particle

- **Rupture of floc**
  - High shear → Restabilized drops

GOOD → BAD

GOOD
Unicel Flotation Unit
Chemical Trials

Oil drop size upstream of chemical addition: $D_{v50} = 25$ micron

Oil concentration into flotation cell (ppmv)

Diameter of oil floc into flotation cell (micron)

Oil concentration out of flotation cell (ppmv)

A: chem 1 @ 16
B: chem 2 @ 12.8
C: chem 2 @ 9.6
D: chem 2 @ 8
E: chem 1 @ 16
F: chem 3 @ 6.5
G: chem 3 @ 9.6
H: chem 1 @ 16
(injection conc in ppmv)
The Effect of flocculating Agents on Flotation

Feed oil drop size $D_{v50} = 25$ micron

Effluent oil drop size $D_{v50} = 14$ micron
(compare with Mars Wemco Effluent $D_{v50} = 6$ micron)

Unicel: 3 min res time

Without chemical, the separation efficiency is 23 %.

With proper chemical selection and dosage, the separation efficiency increases to $> 80 \%$.

Note the presence of flocs of oil drops in the range of 64 to 84 micron.
Chemical mixing / time / concentration:

Turbidity is a measure of flocculation and settling – the lower, the better.

Longer time or higher concentration can overcome poor mixing but with adverse consequences – gunk, accumulation, organic and chemical scaling.

**Chemical & Dosage (mg/L)**

<table>
<thead>
<tr>
<th>Chemical</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>24</td>
<td>12.8</td>
<td>6.7</td>
</tr>
<tr>
<td>26</td>
<td>26</td>
<td>13.9</td>
<td>7.3</td>
</tr>
<tr>
<td>28</td>
<td>28</td>
<td>15.0</td>
<td>7.8</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>16.0</td>
<td>8.4</td>
</tr>
<tr>
<td>32</td>
<td>32</td>
<td>17.1</td>
<td>8.9</td>
</tr>
<tr>
<td>34</td>
<td>34</td>
<td>18.2</td>
<td>9.5</td>
</tr>
</tbody>
</table>
... but with chemical, capture efficiency improves significantly, particularly for large bubbles:

![Graph showing capture efficiency vs. bubble diameter with and without chemical](image)

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.
Problem:

Good bubble distribution, good froth, poor oil drop attachment and capture.

Best Practice:

Best Practice: spreading for $0 \leq SC$ tension

$\gamma_{tg} = \gamma_{wg} - (\gamma_{ow} + \gamma_{og})$

$SC$ : spreading coefficient

$\gamma$ : interfacial tension

$SC > 0$ for spreading
Other Factors:

Besides chemical, a bit of mild 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 suppresses secondary motion and eddies.

Coalescing elements near the top provide surface area for oil drop coalescence.
This concludes the section on chemical treating

The next section is about equipment

Are there any questions?
Types of Flotation Units:

A. horizontal multistage
   1. mechanical induced gas
      a) underflow weir (e.g. Wemco)
      b) overflow/underflow weirs (e.g. Cica, Cameron ISF)
   2. hydraulic induced gas
      1. submerged venturi (e.g. Enviro-Tech Systems)
      2. external venturi (Petreco)
      3. dissolved gas (mostly used downstream)

B. vertical
   1. hydraulic induced gas
      a) internal (submerged) venturi (e.g. Versaflo)
      b) external venturi eductor
         i. bottom feed co-current (e.g. Unicel)
         ii. bottom feed counter-current
         iii. top feed (e.g. Epcon)
      c) multistage (e.g. TS Technologies)
   2. dissolved gas
      a) external pump
         i. bottom feed co-current
         ii. bottom feed counter-current
         iii. top feed (e.g. Siemens SpinSep)
Wemco Depurator was the original IGF design introduced to the oilfield in the 1960's. Typical gas blanket pressure is roughly 0.5 to 4 ounces.
Horizontal Multi-Cell Hydraulic Induced Flotation:

Enviro-Tech Systems – Submerged Eductor
Klimpel (Flotation) Kinetic Analysis:

\[
\frac{C_n}{C_{in}} = \left[ \frac{1}{1 + kt} \right]^n
\]

\[ E = 1 - \left[ \frac{1}{1 + kt} \right]^n \]

\( k \) = kinetic rate constant (typically 1.2)
\( n \) = number of cells (typically 4)
\( t \) = flotation cell residence time (typically 1 minute)

Oil removal is a function of physical and chemical characteristics (kinetic rate constant), residence time and number of cells.

Note: single cell efficiency is only about 50%.

Wemco Performance:

Mars platform
Deepwater GoM

Note: average oil separation efficiency was 92%

Feed to Wemco was from the discharge of free water knockout.
The inlet and outlet oil concentrations are shown in the blue and purple dots and the left hand scale. The target oil concentration in the discharge was 40 mg/L which was achieved most of the time. Relatively high oil concentrations were fed to the unit. Also, there was significant variation in oil concentration to the unit. Oil removal efficiencies were generally good but somewhat variable, likely due to the variation in oil content going in.
Wemco efficiency – as the oil content goes down, as a result of better upstream processing, the average drop size goes down as well. This results in less oil, and smaller drops being fed to the Wemco. The net result is a decrease in Wemco separation efficiency.
This figure suggests that drop size as small as 3 to 6 micron are effectively removed in a Wemco model flotation unit, with the use of chemical, and 2 % reject.

**Fig. 6** – Typical oil-drop size distribution curves for experimental IGF machine study (rotor diameter = 16 in., rotor speed = 225 rpm, engagement = +1 in., chemical concentration = 5.3 cm³/m³, skim rate = 17 gpm, submergence = 3½ in., inlet oil concentration = 210 mg/dm³, flow rate = 816 gpm).

Ref.: Leech et al., JPT(1980)
Wemco reject flow rate automation – an automated feedback control system was installed in order to reduce the variability in the reject flow rate. Much of the variability was due to sea state. Regardless of the source, the feedback system was very effective in eliminating the variability and allowing the Wemco to operate with a steady reject flow rate.
Wemco level control: a flow meter (FI) sends the flow rate to a PID controller which compares the measured flow rate to a set point. The controller then sends a signal to the level controller for the effluent discharge which adjusts the level control set point.
Dissolved Gas Flotation

Configuration is similar to that of dispersed gas flotation.

Effluent water is recycled. Gas is dissolved (or injected) into the effluent water and fed into the flotation unit. Unit is designed to handle recycle water volume.
Fluid Flow / Hydrodynamics:

Illustrative example: since most horizontal flotation equipment is large, it is typically designed for high flow rates. This creates a cross flow. Bubbles that are too small to rise against the cross flow get swept from one chamber to the other and eventually to the discharge without providing flotation.

On-shore installations (e.g. refineries) operate at much lower flow rates and therefore much lower bubbles size can be used, such as dissolved air flotation.

Box-style units tend to have quite a bit of “fugitive emissions.”

Pressure vessels eliminate the loss of hydrocarbon vapor to the atmosphere, but typically do not have view ports.
Cylindrical WEMCO ® Depurator ®
Hydraulic Skimming
• No Internal Skimmer Assembly
• Skims by Fluid Motion
This is the end of the section on Horizontal Multi-Stage Flotation

Next Section: Vertical Flotation

Are there any questions?
Vertical Flotation:

- Petreco Unicel (now Cameron)
- Monocep SpinSep (now Siemens)
- Cetco CrudeSep (now Cetco-Monarch)
- Natco VersaFlo (now Cameron)
- EPCON CFU (now MI Swaco)

- Most vertical flotation units are intended to be smaller and to weigh less than a Wemco, and therefore typically have lower residence time and are only single or “double” stage.

- Care is usually taken to ensure small bubble size. Dissolved gas, which gives very small bubbles can be effective.

- To overcome the limited residence time and the lack of multiple stages, some units have coalescing elements in addition to flotation, which require that the oil be evaluated for stickiness.

- Design considerations include:
  - means of generating and introducing the bubbles
  - configuration for feeding and discharging the water and oil.
Weight of Horizontal vs Vertical Flotation:

![Graph showing weight (metric tons) vs capacity (BWPD) for different types of flotation systems. The graph compares Natco VersaFlo, Natco horizontal IGF, Unicel, and Epcon CFU.]
Types of Flotation Units:

In the mechanical design of a flotation unit, there are a few practical considerations.

First, the oily water must be introduced in a way that does not disrupt the flotation process.

Second, the oil and clean water must be discharged in a way that does not allow contamination with the feed and that does not disrupt the process.

Third, the overall weight and space must be as low as possible, which achieving a high separation performance.
Unicel –
Hydraulically Induced Gas Flotation Bottom Feed Co-Current
Unicel Vertical Induced Gas Flotation Unit - Pumptless Unit

Typical designs provide sufficient pressure for the inlet produced water (> 45 psig) to charge the eductor, thus typically no recycle or inlet pump is required.

High volume / low feed pressure system do require a recycle pump.

Water with dispersed gas bubbles enter at bottom of riser pipe.

There is a coalescing element at the top of the pipe.

An oily froth is spilled over the weir into the skim through, which is emptied periodically by open a discharge valve.
An eductor may be followed downstream with a dispersing element such as a static mixer.

Induced gas flow rate is calculated using Bernoulli’s principle.
Unicel performance example:

Single cell, external recycle provides flow through a venturi

Design feed flow rate: 16,000 m³/day
Design residence time: 34 seconds at design flow rate
Design gas / water ratio: 0.14 m³ gas / m³ water

after chemical optimization
Epcon (CFU)  
(now MI Swaco, a division of Schumberger)
Epcon CFU Performance:

<table>
<thead>
<tr>
<th>inlet (mg/L)</th>
<th>sep eff (%)</th>
<th>outlet (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>63</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>50</td>
<td>20</td>
</tr>
</tbody>
</table>
North Sea vs Deepwater GoM Liquids Processing Systems:

**GoM**
- Cooler fluids
- 2-phase / 3-phase
- More shear

**North Sea**
- Hotter fluids
- All 3-phase w/ hydrocyclones
- Less shear

Field data together with modeling demonstrates why flotation is required in the deepwater GoM but not in the North Sea – both shear and fluid temperature are significant factors.

Ref: Walsh & Georgie SPE – 159713
Siemens SpinSep Dissolved Gas Flotation:
TS Technology – Multistage Vertical Induced Gas Flotation

Diagram showing a vertical flotation system with labeled parts:
- Water Inlet
- Gas Injectors
- Recycle Gas Line
- Separated Oil
- Oil Bucket
- Inlet Diverter Plate
- Gas Bubbles
- Lower Diverter Plate
- Oil Discharge
- Treated Water Outlet
- Recycle Water Pump
- Gas Injectors
IGF vs GFT (Microbubble):

Theoretical analysis indicates that hydrocarbon removal should improve with increasing bubble concentration and reduced bubble diameter. This is the principle behind DGF, Epcon, GFT.

**IGF (Wemco):**
- Typical gas/water ratio: 8.5 m³ gas/m³ water
- Typical gas bubble size: 100 to 1,000 microns

**GFT:**
- Typical gas/water ratio: 0.12 m³ gas/m³ water
- Typical gas bubble size: 20 microns

Comparison of number of bubbles:

\[
\left[ \frac{v}{d^3} \right]_{GFT} / \left[ \frac{v}{d^3} \right]_{IGF}
\]

<table>
<thead>
<tr>
<th>IGF Bubble Size</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>380</td>
<td>100</td>
</tr>
<tr>
<td>1000</td>
<td>2000</td>
</tr>
</tbody>
</table>

Depending on the IGF bubble size, GFT has potentially a much higher number density of bubbles.

However, field performance of a Wemco is difficult to improve upon. This is due to having windows that allow operators to see what is happening for troubleshooting and to make adjustments, and a multistage design (Klimpel eqn). These are important factors.
**Vertical Flotation System Key Benefits:**
- Small footprint.
- Typically high mechanical reliability since there are no internal moving parts.
- Usually responds well to upsets and has good turn down capability.

**Vertical Gas Flotation Systems Key Drawbacks:**
- Typically low oil removal efficiency (roughly 50 to 60 % per stage)
- Rely on coalescence which can be rendered useless when oily solids are present
- This technology is best deployed downstream of other “coarse” separation equipment e.g desander and/or deoiler hydrocyclones.
- Vertical gas flotation units require continuous injection of a suitable water clarifier/flotation aid polymer chemicals to achieve high water treatment specifications
- There is usually no “quiet zone” for chemical reaction
- Feed water streams with high clay and silt fines content can be a problem if they settle inside the gas flotation vessel and oil box as the sediment can reduce residence time and cause maldistribution of gas.
- This type of design does not react well to flow surges. Performance tends to deteriorate rapidly under these conditions.
- For applications where Calcium Naphthenate is present blockages can be expected within the vessel internals.
This is the end of the section on Vertical Flotation

Next Section: Modeling

Are there any questions?
Sweep Factor:

\[ SF = A_{gas} \times F_{gas} / A_{cell} \]

**SF**: Sweep Factor \( (m^2 \text{ gas/m}^2 \text{ cell min}) \)

- \( A_{gas} \): cross-sectional area of bubbles per unit volume of gas \( (m^2 \text{ gas/m}^3 \text{ of gas}) \)
- \( F_{gas} \): gas volumetric flow rate \( (m^3 \text{ gas/min}) \)
- \( A_{cell} \): sectional area of contact cell \( (m^2) \)

**SF**: the cross-sectional area of gas that sweeps through a cross-section of the flotation cell in a minute

\[ A_{gas} = \frac{\left( \frac{\pi}{4} \right) d_b^2}{\left( \frac{\pi}{6} \right) d_b^3} = \frac{3}{2d_b} \]

Sweep Factor:

\[ SF = 1.5 \times \left( \frac{F_{\text{gas}}}{A_{\text{cell}}} \right) / d_b \]

SF: the cross-sectional area of gas that sweeps through a cross-section of the flotation cell in a minute
Quantitative Modeling:

Ideal Continuous Stirred Tank Reactor:

\[ V \frac{dC}{dt} = C_{in}Q - CQ - kCV = 0 \]  
(at steady state)

\[ C = C_{in} / (1 + kV/Q) \]

- \( C \): concentration of oil (no. oil drops / m³)
- \( Q \): flow rate (m³/sec)
- \( V \): volume of contact cell (m³)
- \( k \): reaction rate constant (1/sec)
Quantitative Modeling con't – Separation Efficiency:

Ideal CSTR: \( C_{\text{out}} = C_{\text{in}} /(1 + kV/Q) \)

by definition: \( E = (C_{\text{in}} - C_{\text{out}}) / C_{\text{in}} \)

substituting:

\[
E = \frac{kV/Q}{(1 + kV/Q)} \quad \rightarrow \quad 1.0
\]

as \( kV/Q \) becomes large
Quantitative Modeling con't – Comparison with Arnold & Stewart:

Arnold & Stewart: \[ E_{AS} = \frac{k_{AS}}{(Q + k_{AS})} \]

CSTR Kinetic Theory: \[ E = \frac{kV/Q}{(1 + kV/Q)} \]

comparing CSTR Kinetic Theory with AS gives :
\[ k_{AS} = kV \]
Quantitative Modeling con't –
Comparison with Arnold & Stewart:

Arnold & Stewart give:

\[ k_{AS} = k_p \pi D^2 \left( \frac{H}{d_b} \right) \left( \frac{Q_g}{Q_w} \right) \]

- **D**: diameter of contact cell (m)
- **H**: height of contact cell (m)
- **Q_g**: volumetric flow rate of gas (Sm3/sec)
- **Q_w**: volumetric flow rate of water (m3/sec)
- **d_b**: bubble diameter (m)
- **k_p**: collision & capture efficiency

Note the similarity with the Flux Factor:

\[ N_F = \left( \frac{H}{d_b} \right) \left( \frac{Q_g}{Q_w} \right) \]

\[ k_p = E_{coll} \times E_{capt} \times (1 - E_{attach}) \]
Calculation of Collision Efficiency:

\[ E_{\text{coll}} = \pi r_c^2 / \pi r_b^2 = d_c^2 / d_b^2 \]

- \( E_{\text{coll}} \): collision efficiency
- \( d_c \): collision diameter
- \( d_b \): bubble diameter

Clean bubble surface.
Rise velocity = 3/2 Stokes Law

\[ E_{coll} = 3 \left( \frac{d_p}{d_b} \right) \]

Sutherland Eqn

Stokes Law – solid particle or contaminated bubble surface, e.g. surfactant coated bubble

\[ E_{coll} = 3 \left( \frac{d_p}{d_b} \right)^2 \]

Gaudin Eqn

Fig. 2. Calculated and experimental collision efficiency versus bubble diameter. The potential flow curve shows $E_c$ calculated according to the Sutherland Equation (Eq. (5)). The Stokes curve shows $E_c$ calculated by Gaudin's Equation. Eq. (7)

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

\[ t_c = \frac{V_c}{Q_w} \]

\( t_c \) = 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)

\[ \text{number of bubbles per unit area per unit time} \approx \frac{Q_g}{A_c d_g^3} \]

\( d_g \) = diameter of gas bubble (micron)
\( Q_g \) = volumetric flow rate of gas (m³/minute)
\( A_c \) = cross sectional area of the contact cell (m²)

\[ \text{cross sectional area of bubbles} \approx d_g^2 \]

Combining these terms gives the Flux Factor:

\[ N_F = \frac{H_c}{d} \left( \frac{Q_g}{Q_w} \right) \]

\( H_c \) = height of the contact cell

The Flux Factor is a dimensionless parameter which characterizes the mechanical design of a flotation unit.
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 \((E_{12})\) can be included in the correlation. Here we use Parkinson, Ralston model.

\[
(H/d) \times \left(\frac{Q_g}{Q_w}\right) \times E_{12}
\]

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.
Gas Flotation Technology Summary

**Advantages**
- Well established technology
- Can remove suspended solids as well as oil
- Good turndown (longer residence time, improved separation)
- Relatively low OPEX costs
- Highly effective when used with chemical aids
- Can cope with a wide range of oil feed concentrations

**Disadvantages**
- Horizontal Units are motion sensitive, vertical are less-so
- Units tend to be large and bulky
- Maintenance can be high
- Some designs use moving parts
- Larger solids particles can settle at the bottom of the unit
- Eductors, venture can become fouled or plugged

For high water flow rates, may need to install numerous units in parallel. Smaller models (<85 kBPD) tend to work better. Should also consider series arrangement.
Best Practice for Flotation Units:

- Use gas blanket rather than atmospheric air to avoid corrosion, scale
- Skimming under varying flow conditions
- Use adjustable skimmers to optimize skimming of oil at surface
- Clean eductors regularly since they can become clogged with scale
- Install anti-motion baffles where required
- Performance is sensitive to chemicals, over treating, contamination, solids
- Do not use sparge tubes

Ref: Jane Pederson, Allan Lawrence, Zara Khatib, “Best Practice in Produced Water Treatment, SIEP 99-5806
Questions?

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