Efficiency of Oil / Water Separation Controlled by Gas Bubble Size and Fluid Dynamics within the Separation Vessel

Douglas W. Lee, Dr William .J.D Bateman and Nicholas Owens - GLR Solutions Ltd.

ABSTRACT

This paper reviews the current state of gas flotation within the Oil & Gas industry and considers why the industry is now demanding higher efficiency separation than is currently in use. The major principles behind the design of high efficiency gas flotation are discussed and it will be demonstrated that the control of gas bubble size along with fluid dynamics within the separation vessel are the primary mechanisms for increasing oil removal efficiency. Finally, examples of this new generation of gas flotation technology are introduced.

1.0 INTRODUCTION

The use of gas flotation based technologies for the separation of oil from water has been in commercial application for over 100 years, with the first US patent for oil flotation issued to Elmore in 1901. Gas flotation is now widely accepted within the Oil and Gas industry as the preferred method for removing suspended oil (free oil) from produced water when oil concentrations need to be reduced from several hundred parts per million down to sub twenty parts per million .

Gas Flotation has proven its commercial value in the role of "secondary" produced water treatment however, a number of factors have converged to drive industry demand for higher performance flotation technology. The main factors driving the need for improvements include:

- Increased volumes of produced water from older reservoirs.
- Increased use of Enhanced Oil Recovery (EOR) techniques which tend to create produced water that is more difficult to treat.
- Increased production from unconventional reserves (heavy oil, oil sands, etc.) resulting in produced water that is more difficult to treat.
- Increased use of Floating, Production, Storage and Offloading systems (FPSO) and deepwater production platforms where space is increasingly valuable and there is potential for wave motion to impact on separation vessels.
- Increased demand for the re-use of produced water in applications (re-injection, steam generation, etc.) where residual oil and solids would be detrimental to downstream equipment or reservoirs.
- More stringent environmental regulations throughout the world.

The impact of these factors is that gas flotation equipment that achieved acceptable performance several years ago, now no longer fully meet industry requirements.

If industry is to develop and implement improved designs of flotation equipment it is important to have a proper foundation of the critical design factors for high performance flotation. In particular it is necessary to improve on those areas where previous generations of equipment have failed or under performed.

2.0 CRITICAL DESIGN ELEMENTS FOR HIGH PERFORMANCE FLOTATION

While this is not a complete summary of all design parameters, this paper focuses on those areas of flotation that the authors feel are the most critical, and in general have the most potential for improvement in the majority of currently commercialized gas flotation packages. It is these technical issues that should be considered when evaluating or selecting commercially available gas flotation equipment, or when attempting to optimize older generation installations.

2.1 Contact of Gas Bubble and Oil Droplet

The performance of a gas flotation process is primarily a function of the probability of contact between a gas bubble and an oil droplet. In the simplest of terms, an oil droplet cannot be floated to the surface by a gas bubble if the two particles do not come into contact. The probability of contact can be improved by several factors. These include the presence of uniformly distributed bubbles throughout the contact zone, as well as a high density of bubbles with small interstitial spacing between bubbles.

Uniform Distribution of Bubbles - There are several challenges in achieving a uniform distribution of gas bubbles within a gas flotation vessel. The first is dealing with multiphase flow in a highly dynamic environment, i.e. bubbles are rising vertically as water is flowing horizontally and often downward. Common techniques for the creation of bubbles utilize eductors and various types of distribution headers. These headers, or nozzles, are only effective in localized distribution, but thereafter rely on the hydraulic flow to distribute bubbles in zones farther from the nozzle or header. Too often there are significant zones of limited or no bubbles in these types of flotation vessels (see Figure 1).

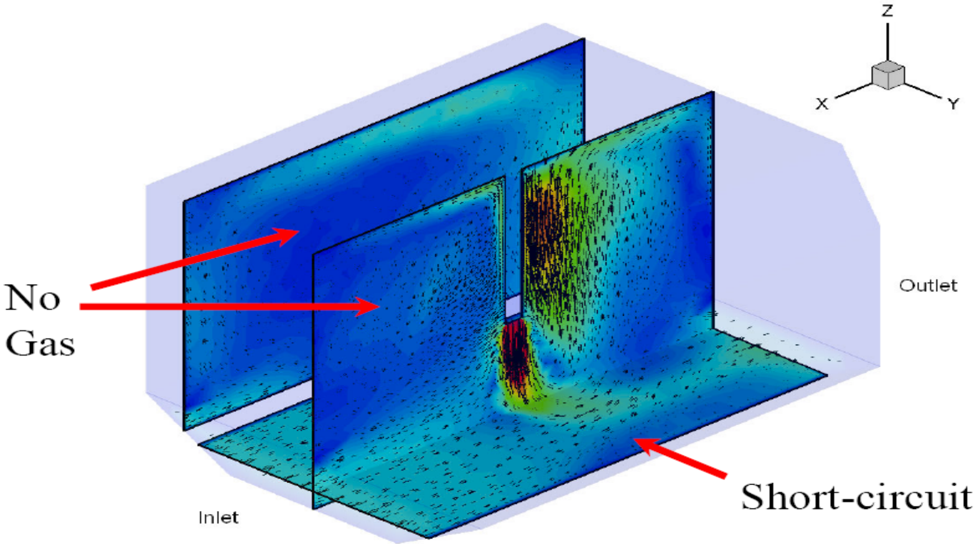

Figure 1 - Typical Multiphase Flow in a Conventional Horizontal IGF Cell

The second challenge is that as bubble size increases the resulting jet from a distributor becomes more buoyant, thereby reducing the radius of influence around the nozzle. This design flaw is prevalent in flotation vessels that utilize large bubbles created by an eductor (venturi). Smaller bubbles generated by scaleable technologies (microbubble generators) where bubble size remains constant are easier to distribute uniformly as they are less buoyant and carry farther in the flow.

High Density Packing of Bubbles - Performance of gas flotation technologies can be significantly improved by modifying the packing density of gas bubbles within the bubble/droplet attachment zone. The objective is to generate as many bubbles as possible within a fixed volume of water and within a fixed physical location inside the vessel. It is helpful to draw an analogy to a sand filter where the grains of sand packed within the filter act to physically obstruct solids flowing past them. Removal efficiency improves as the grains of sand become more closely packed together, or the grain size becomes smaller. This same principle can be applied within a flotation vessel by using very small gas bubbles that are closely packed together. A study of the optimal distribution of bubbles created from a fixed volume of gas shows that in a confined system there is a linear and direct relationship between bubble size and the interstitial space between them (see Figure 2). This affirms that for optimal separation it is desirable to create very small bubbles, which are narrowly spaced, thus producing a high probability of a collision with an oil droplet.

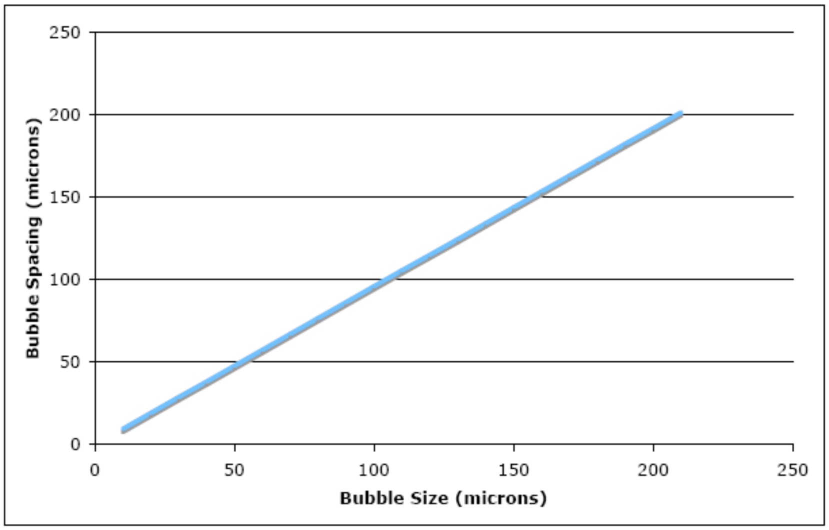

Figure 2 - Relationship between Bubble Size and Bubble Spacing in a Confined System

2.2 Attachment of Gas Bubble to Oil Droplet

Once a gas bubble and oil droplet have engaged (collided) it is desirable to keep the two particles in contact with each other until they reach the surface and disengage. If disengagement occurs prior to the oil droplet reaching the surface the rise rate of the oil droplet will decrease and there is potential for it to become caught in a downward current and pass through the separator unhindered. Disengagement prior to the surface also creates a demand for another engagement event, which has a decreased probability of occurring due to the reduced amount of possible contact time as the parcel of water progresses through the separator. A number of factors influence the type of attachment that occurs and the probability for disengagement of the gas bubble and oil droplet. These include:

Type of Attachment - When a gas bubble contacts an oil droplet there are two likely outcomes

a) Adhesion – This is intimate contact at a specific localized point between the gas bubble and oil droplet (see Figure 3). Adhesion is a relatively weak attachment and the ability for this mutual contact to continue as the combined bubble/droplet rises towards the surface is a function of the surface area that is in contact, along with hydraulic considerations such as turbulence and drag resulting from its rise velocity. As the magnitude of difference in particle size increases between the droplet and the bubble the strength of adhesion decreases due to increased buoyancy of the bubble and decreased surface area for attachment.

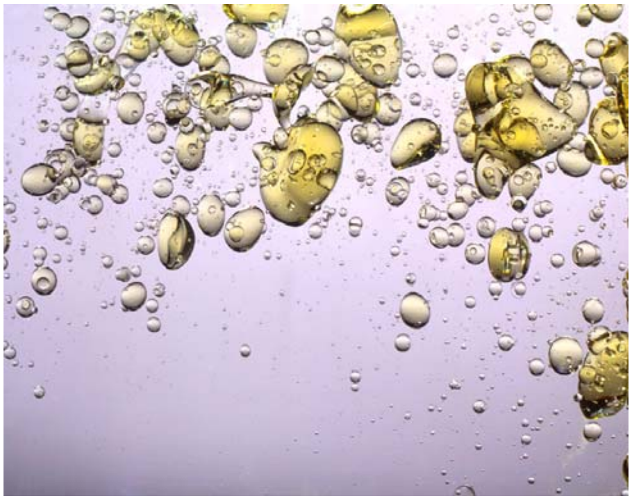

Figure 3 - Adhesion of Gas Bubbles and Oil Droplets

b) Encapsulation – This is when the oil droplet surrounds the gas bubble thereby exposing the entire surface area of the bubble to the oil (Figure 4). Encapsulation is a much stronger type of attachment due to the much larger surface area of contact. Flotation is a physical process and it is the friction on the surface of the two bodies that allows the gas bubble to drag the oil droplet to the surface. The larger surface area in direct contact with the oil, that occurs with encapsulation, allows for additional friction and a higher probability that the bubble and oil remain in contact. The probability for encapsulation occurring is a function of a number of factors including the physical properties of the oil, and the angle and velocity of impact. However, perhaps the largest determining factor is the relative size of the gas bubble compared to the oil droplet. It is much easier for a small gas bubble to be encapsulated by an oil droplet than a large one.

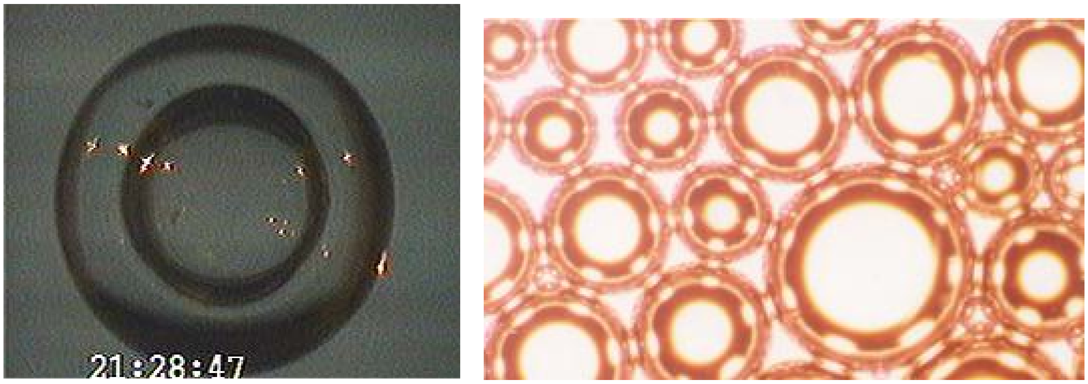

Figure 4 - Encapsulation of the Gas Bubble by Oil Droplet

<u>Surface Area for Attachment</u> - Regardless of the type of attachment that occurs, the strength of the bonding is determined by the surface area of the contact region between the gas bubble and oil droplet. Figure 5 illustrates how the total available surface area dramatically increases as the size of the bubble decreases for a fixed volume of gas. This therefore implies that smaller bubbles are more desirable due to the attachment bonds they are likely to create being far more numerous than those of larger bubbles. Figure 5 illustrates the diminished return of surface are as bubble size increases above 75 microns, thereby severely impaired surface area for attachment.

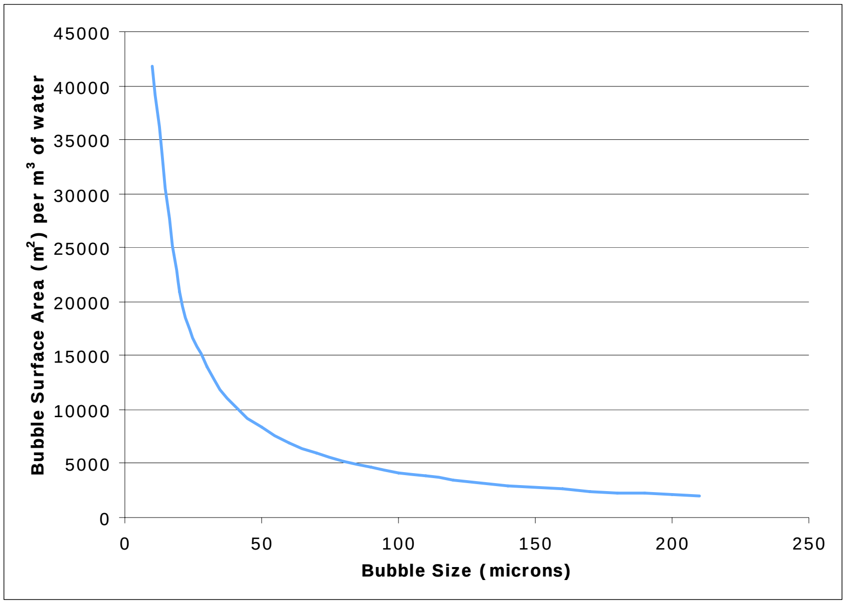

Figure 5 - Surface Area vs. Bubble Size

Rise Velocity Impacts – The rise velocity of a gas bubble will impact the following:

a) Time of Contact - how long a bubble will stay attached to an oil droplet
b) Type of Attachment - adhesion versus encapsulation
c) Fluid Behavior – Large bubbles have a localized impact on fluid flow as they create turbulence in the wake immediately behind them

Figure 6 compares the rise velocity of methane bubbles to oil droplets (0.95 Specific Gravity, API 18) for a variety of particle sizes. It can be seen that even very small gas bubbles rise much faster than large oil droplets, and as the size of the gas bubble increases the magnitude of this difference increases dramatically. Very early in this continuum of increasing particle size the magnitude of velocity difference between the two becomes so large that there is very little time for contact, thus leading to weak attachment. In addition to this, the column of water surrounding the large bubbles becoming turbulent and the process becomes ineffective at removing small oil droplets due to their re-entrainment in effluent water.

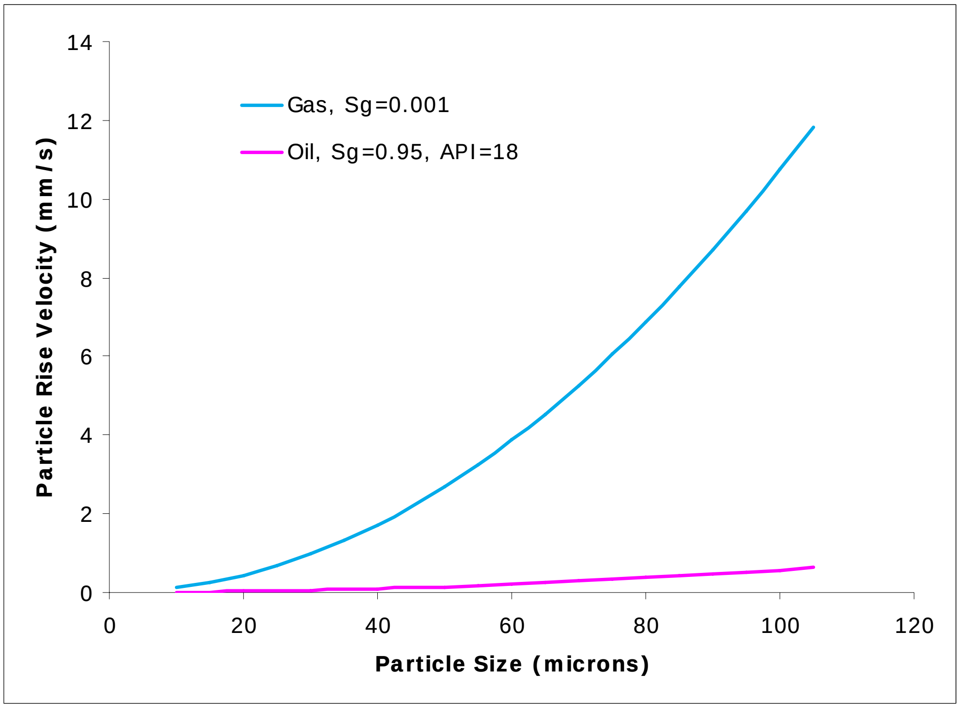

Figure 6 - Rise Velocity Comparisons (Methane Bubbles vs. 0.95 SG Oil Droplets)

Another important phenomenon that is also worth noting at this stage is coalescence. Gas bubbles of any size when in a solution will tend to come together and coalesce, forming larger bubbles. This is an inevitable process that occurs, regardless of bubble size, and further highlights the need to have very small gas bubbles at the commencement of the process. Coalescence can also have a positive effect on the system if two gas bubbles come together that are already attached/encapsulated with oil. The oil droplets will then have an increased probability of joining together and, as large oil droplets are generally easier to remove, the phenomenon can be exploited to an advantage.

2.3 Fluid Dynamics

A number of differing fluid flow conditions within flotation vessels will impact oil removal efficiency. Advancements in the field of Computational Fluid Dynamic (CFD) modeling, and in particular the development of multi phase flow modeling techniques, have dramatically improved the ability to identify and improve fluid dynamics inside vessels and thereby the performance of these vessels as separators.

The primary fluid dynamic conditions that must be considered and optimized whilst designing separators are generally considered to be:

Retention Time & Short Circuits – CFD analysis, conducted in 2006, of the internal design of many commercially available gas flotation vessels showed a prevalence for short circuits and sub-optimal flow patterns. This resulted in retention times that were significantly less than the theoretical maximum. A common problem with many designs was the method of flow between chambers. The use of partial inter-chamber dividing walls, or open passages, with the passage being at the base of the wall caused undesirable flow patterns and effects. The CFD indicated that a portion of the flow along the base of the vessel tended to short circuit between cells, thus drastically reducing the residence time and exposure of bubbles of the main flow. This reduced retention time decreases the oil removal efficiency. Alternative internal designs with complete wall isolation interrupted these linear flow paths and were demonstrated to result in retention times much closer to the theoretical maximum.

Oil Re-entrainment - Turbulence inside vessels can create large shear forces that strip oil droplets from the gas bubbles they are attached to. There is then a possibility for these oil droplets to become re-entrained in the main flow and successful separation is prevented from occurring. The same fate can also occur to oil droplets that have reached the surface, been separated from their gas bubble, but have yet to be skimmed. This is especially prevalent if a large oil layer is allowed to build up and the oil/water interface moves down the vessel. This effect has been observed in several commercial installations and highlights the need for effective separation coupled with a good skimming philosophy and skimming system. Careful placement of vessel internals can assist in solving these problems and reduce to a minimum the likelihood of droplets being re-entrained.

Velocity - Localized high downward velocities flows inside vessels are highly undesirable. As the downward velocity of water increases there is an increased probability that small diameter oil droplets that have a slow rise velocity will get caught within this current and be drawn down and out of the vessel. Some flotation vessel designs (common in many vertical designs) utilize internal columns and structures that act as channels for these high velocity flows and thus have a negative effect on performance. CFD analysis has clearly shown this and attention to velocity at all points within the vessel has been demonstrated to improve oil removal efficiency.

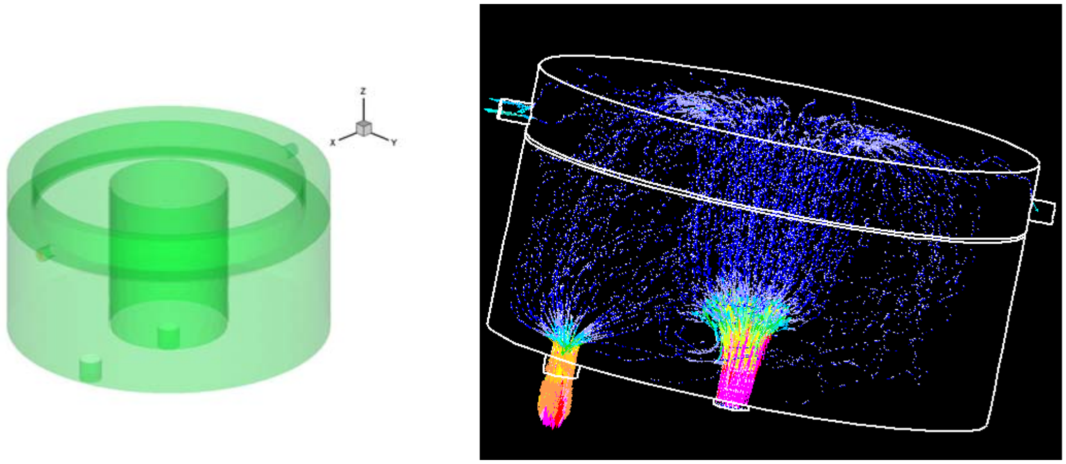

Figure 7 - Vertical IGF with Internal Column and a Short Circuit

Water Trajectory - To help avoid short-circuiting and re-entrainment issues attention needs to be paid to the direction and velocity that an inlet stream is introduced into a chamber. CFD has shown that jets should not be aim directly at the surface as it is desirable to limit turbulence near the oil interface. Nor should they be directly horizontal or vertically downwards as this encourages short-circuiting due to these pathways intersecting the chamber outlet. It has been found that the optimum trajectory is between 30-60 degrees inclination from the horizontal as this disrupts the surface the least and minimizes the effects of short-circuiting and re-entrainment.

2.4 Sequential Removal

Removal of oil using a sequence of isolated chambers is an established method for achieving significant improvements in oil removal. Fundamentally the factor that governs the rate at which oil is removed by gas-floatation is the rise velocity of oil and gas particles, in particular the rise velocity of the combined particles, which is a function of size, gravity, water viscosity and particle density. Thereafter all that is needed is time; so the division of a chamber into several sub-units while retaining the same overall retention time for the entire vessel should not in itself lead to an improvement. To illustrate this, consider

$$r = \frac{-dC}{dt} = k\theta C \tag{1}$$

where C is the oil concentration, *t* is residence time per chamber, *k* is an oil removal constant (min-1), θ is a chamber cell constant related to how efficient any one chamber is at removing oil. This is also a first order differential equation which is solved by a rearrangement to give

$$\int \frac{1}{C} dC = \int k\theta dt \tag{2}$$

The constant of integration is solve for by assuming that the oil concentration leaving a chamber (C_{out}) will equal that entering (C_{in}) when the chambers residence time is zero (*t=0*). This yields

$$\frac{C_{out}}{C_{in}} = \frac{1}{e^{k\theta t}} \tag{3}$$

or for the purposes of a multi-chamber design, the concentration in the n^th^ chamber, C_n, is

$$\frac{C_n}{C_{in}} = \left(\frac{1}{e^{k\theta t}}\right)^n \quad \text{or} \quad \frac{C_n}{C_{in}} = \frac{1}{e^{nk\theta t}} \tag{4}$$

Clearly you get the same result if you double the number of chambers (*n*) and half the residence time per chamber (*t*). However, data from both laboratory and commercial scale gas flotation equipment of a variety of designs conflicts with this conclusion as oil removal efficiency does reliably improve with an increased number of chambers.

Further review reveals that these equations have assumed perfect hydraulic conditions, such that both *k* and θ remain the same for each chamber. This is unlikely when the initial concentrations of oil are high, which will cause the quantity of oil skimmed in the first chamber to be significantly greater than that skimmed in subsequent chambers. The impact this has on the oil removal constant, *k*, can be debated, however the overall chamber efficiency will be lower when there are large deposits of oil at the surface due re-entrained back into the main flow. The other key advantage of a multi-chamber design is that a fresh stream of bubbles can be mixed with the flow as it transfers from one chamber to the next. This has a direct improvement on *k*, which can not easily be replicated in a single chamber design where is it difficult to evenly distribute the bubbles (see section 2.1). As mentioned previously in this paper, poor internal design can have a detrimental effect on overall oil removal efficiencies (i.e. a design with lots of short circuiting and wall channeling will not perform as well as a design with none). These equations in their current form do not take this into account, further supporting the argument of a modified constant which is related to individual cell performance.

Therefore equation (4) becomes

$$\frac{C_n}{C_{in}} = \prod_{i=1}^{n} \exp(-k_i \theta_i t) \tag{5}$$

Alternatively the cumulative removal efficiency (CRE) is

$$CRE = 1 - \prod_{i=1}^{n} \exp(-k_i \theta_i t) \tag{6}$$

For the purposes of defining these constants (*k* and θ) for a general, unknown, inlet oil concentration only the product $K_i = k_i \theta_i$, needs to be considered. From an analysis of various IGF designs [1], product *K* for the fist chamber is estimated to be $K_1 \sim 0.65$, with a higher value of ~0.8 for all subsequent chambers. However, it is important to remember that the performance and selection of *K* (or even *k* and θ) for any one vessel can only be found with individual site tests.

Figure 8 illustrates the cumulative performance of an nth chambered vessel, on the basis of equation (6). For a four chamber unit, with a 1 minute residence time per chamber the overall removal efficiency is over 95%. With a two chamber unit, now with 2 minute residence time per chamber, the removal efficiency drops 94%, whereas a single chamber unit with 4 minutes residence time would only remove 92% of oil.

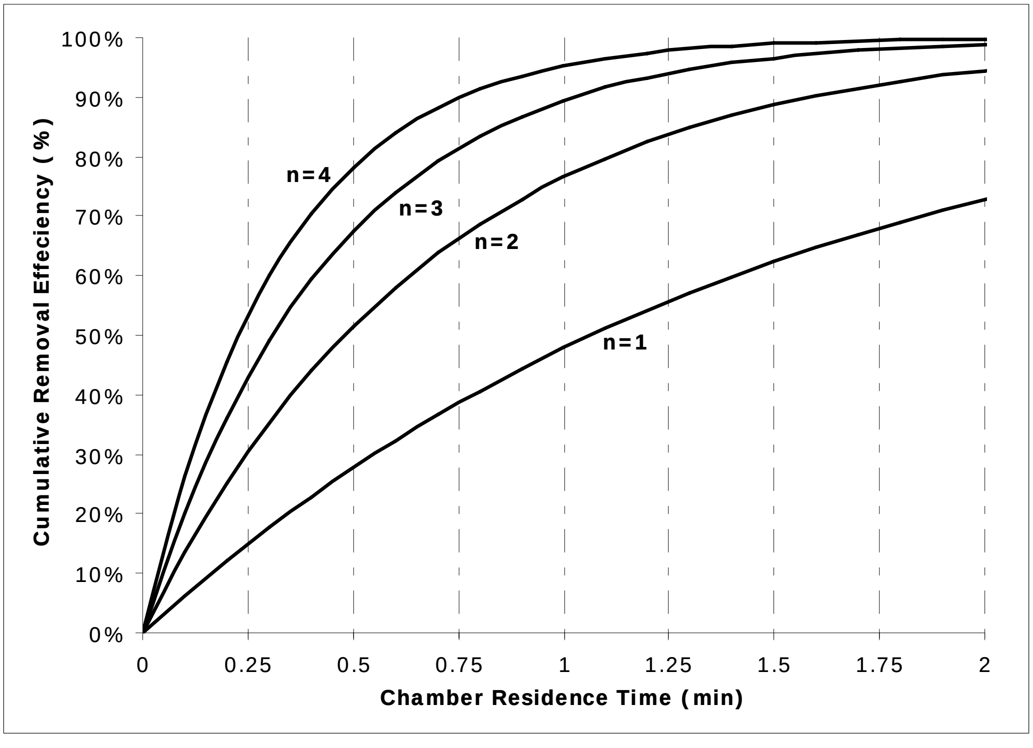

Figure 8 – Flotation analysis of a conventional four cell IGF

2.5 Oil Skimming Method and Location

As previously mentioned, a good skimming philosophy and skimming system are essential to maximize phase separation performance. It has been observed that allowing excessive amounts of oil to build up on the surface can lead to oil re-entrainment, followed by a drop in performance. A common industry technique for skimming in older generation IGF's involved the use of paddle wheels, and other types of mechanical skimmers (Figure 9), to force the oil into the skimming weir. These techniques are not ideal though as a number of negative effects can be observed when they are employed inside vessels. Paddle wheels tend to limit the volumes of oil that can be recovered due to their restricted set points. They are therefore not well adapted to variable feed conditions. The rotating at the surface can also be found to aid re-entrainment due to the turbulence they cause.

Modern skimming designs have adapted to utilize hydraulic skimming mechanisms where surface flow patterns and velocity drive oil over into a collection trough (oil weir). These designs have improved the amount of oil that can be skimmed under variable inlet flow rates and tend to re-entrain less oil than mechanical designs. Performance is unique to each design and careful placement of oil weirs relative to the chamber inlets & outlets and turbulent zones remains critical.

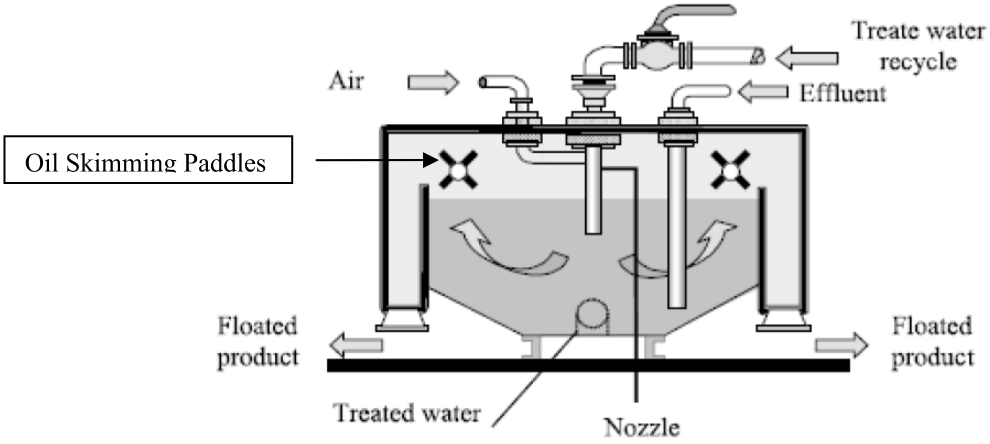

Figure 9 - Mechanical IGF with Oil Skimming Paddles

3.0 SUCCESSFUL APPLICICATION OF THE SCIENCE OF FLOTATION

In the real world gas flotation equipment is based on vessels, piping, and pumps rather than scientific formulas, computer models and CAD drawings. It is the application of the science that truly makes the difference between average performance and high performance. It is also critical to consider that from the owners/operators perspective the reliability, size and weight of the equipment is as important and often more important than removal efficiency. Successful application of the science of flotation requires very small bubbles, a vessel with unique fluid dynamic conditions in a small footprint driven by reliable mechanical equipment and controls.

3.1 Bubble Generation

Conventional Bubble Generation - Most current flotation equipment on the market utilize some variation of an eductor (Figure 10) to generate bubbles, followed by some bubble distribution method inside the vessel, usually a nozzle or distribution header. Eductors work by entraining gas due to a pressure drop (Venturi effect) across the suction connection. The magnitude of ΔP and the volume of motive flow determine the volume of gas entrained.

The problem with eductors though is that, bubble size is determined by the diameter of the suction connection. This means that, especially at larger flow rates, bubble size can be very large. For example, a 2" eductor, with a motive flow of 60 gpm and a suction connection of 1.25" would generate a minimum bubble diameter of 1.25" and a mean bubble size significantly larger. As previously discussed large bubbles are not as effective at oil attachment and are difficult to distribute through the vessel. Once you consider that the flow rates for most commercial installations are much larger than this it becomes clear that this is not a high performance solution.

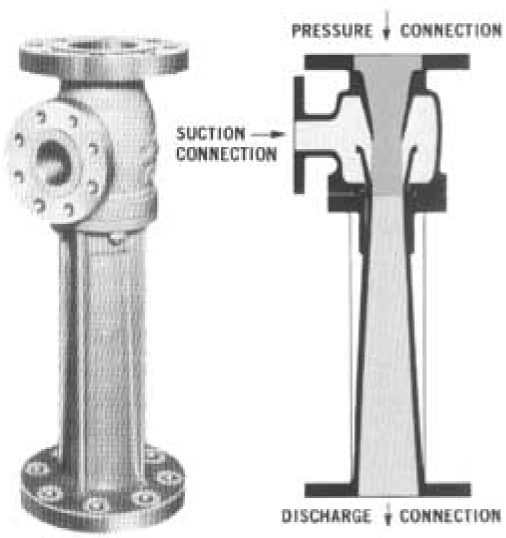

Figure 10 - A Typical Eductor

Micro-Bubble Generation - In recent years new technology has been developed that can allow relatively insoluble gas such as Methane to be entrained into water in the form of micro-bubbles. Micro-Bubbles from these devices have a median diameter of ~30µm, and to operate successfully for gas flotation the bubble size needs to be maintained within a tight and constant range irrespective of the flow rate.

Two commercially proven technologies for this purpose are available, which are capable of consistently producing bubbles with a diameter of ~30µm. The first technology is the Gas Liquid Reactor (GLR™), which utilizes shear and impact forces within a pressurized vessel to generate the bubbles. These devices can be configured to operate at a wide variety of flow rates and are capable of performing over a wide variety of conditions. Generally the physical size of this technology limits its application to land based facilities where size and weight are less critical.

The second technology is the Onyx™ micro-bubble generating pump (Figure 11) which has a unique open impellor design that creates shear forces on a multiphase fluid to create micro-bubbles. The pump capable of self inducing up to 20% of its inlet flow as a gas into its casing, which it then uses to create trillions of bubbles. This gas can either be induced directly from the headspace of a vessel, or supplied via a dedicated pressurized feed.

Figure 11 - Onyx Microbubble Generation Pump

3.2 Vessel Internal Configuration and Design

The optimal vessel design is a function of the process specification, the site specific location of installation and the implementation of the design principles previously discussed. In general offshore facilities are increasingly trending toward the use of vertical vessels due to their smaller footprint and weight while land based facilities have continued to utilize horizontal vessels typically containing 5 internal chambers.

A critical analysis of the bulk of gas flotation equipment commercially in service reveals a general failure to fully implement the design principles for high performance phase separation. For those facilities requiring high removal efficiencies, upset buffering capacity and process reliability it is advisable to implement vessel designs that incorporate the following features.

Horizontal Flotation Vessels:

- Interchamber dividers must be complete walls and not allow short circuiting from one chamber to the next preventing short circuits and retention times significantly shorter than the theoretical maximum.
- Internals should focus on fluid dynamic issues such as velocity, trajectory and turbulence with negative impacts on oil re-entrainment and premature bubble detachment.
- Microbubbles should be utilized for attachment to oil droplets
- Microbubbles must be forced into intimate contact with the entire flow, not just isolated portions of it.
- Mechanical skimmers should be avoided. An opposing water and oil weir setup as utilized in the Revolift™ design is a good alternative as this allows for hydraulic skimming.

Vertical Flotation Vessels:

- Internals should avoid the use of internal columns, packing or structures that accelerate or can create asymmetric flow.
- Increased efficiency can be obtained by using a vertical multichamber arrangement as utilized in the Revolift™ design.
- Microbubbles should be utilized for attachment to oil droplets
- Microbubbles must be forced into intimate contact with the entire flow, not just isolated portions of it.
- Mechanical skimmers should be avoided. An opposing water and oil weir setup as utilized in the Revolift™ design is a good alternative as this allows for hydraulic skimming.

4.0 CONCLUSION

In conclusion both the science and application of gas flotation technologies have improved significantly in recent years. The new generation of microbubble flotation equipment that incorporates the design considerations presented within this paper offer customers a higher level of oil removal efficiency a more robust design capable of better buffering upstream process upsets and the reliability of a hydraulically driven process.

REFERENCES

1. Leech, C.A., Radhakrishman, S., Hillyer, M.J. and Degner, V.R. **1980**. *Performance Evalulation of Induced Gas Floatation Machine through Mathematical Modeling.* Journal of Petroleum Technology, p. 48.