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Compact Induced Gas Flotation as an Effective Water Treatment Technology on Deep Water Platforms

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Abstract

Although induced gas flotation is routinely practiced on fixed platforms, there are special challenges for practicing this technology on deep water platforms. This paper presents an overview of the physical and chemical principals of how induced gas flotation actually works, reviews the special challenges involved in applying induced gas flotation technology on a floating platform, and outlines the process and vessel design requirements for the effective use of compact induced gas flotation on a deep water platform.

The challenges for induced gas flotation on a floating platform include designing compact systems that minimize space and weight requirements, dealing with water that may contain hydrate inhibitors such as methanol, cleaning water with very small (and relatively stable) oil droplet size distributions, cleaning water below the Wax Appearance Temperature, and designing compact flotation cells that are tolerant of slosh-motion. The negative impact of process recycle streams on flotation will be illustrated.

The successful practice of compact induced gas flotation on a deep water platform requires a combination of good overall process design, an understanding of the water chemistry involved, and well designed equipment. An example is given to illustrate how process design considerations can affect the performance of flotation as a water cleaning technology.

Flotation Mechanisms

There are three mechanisms by which oily contaminants are removed by induced gas flotation. These mechanisms operate singly or in combination depending upon the specific characteristics of the produced water and the level of attraction and wetting between the gas bubbles and the oily contaminants. The mechanisms are as follows:

1. Oil coats the rising gas bubbles. This mechanism is operable when the contact angle between the oil and the gas bubble is low (wetting is high).
2. Oil droplets and oily contaminants stick to a gas bubble and rise with it to the surface. This mechanism is operable at moderately low contact angles (modest attraction of oil to gas bubble) and is most efficient when contaminants and gas bubbles are of similar size.
3. Oil droplets and oily contaminants are dragged behind in the wake of a rising gas bubble to the water's surface. This is the weakest interactive mechanism and does not require a low contact angle.

Some authors believe that the third mechanism, although being the weakest, is dominant in most oilfield flotation systems.[1,2]

Mechanical Requirements for Efficient Flotation

For all of the listed flotation mechanisms, efficiency is enhanced by maximizing the number of interactions between the contaminants and the gas bubbles. Interactions are maximized by the following:

1. Uniform distribution of oily water throughout the flotation cell
2. Uniform distribution of gas bubbles throughout the flotation cell
3. Minimizing the size of the gas bubbles
4. Maximizing the size of the contaminants to be removed
5. Maximizing the tendency of the contaminants to remain in contact with rising gas bubbles

Vessel Hydraulics. The first points are related to flotation cell hydraulics. The designs of the inlet and of any baffles that divert flow are critical to insuring that water is well distributed as it flows through the flotation cell. Figure 1 is an example of a horizontal flotation cell design that unsuccessfully attempted to use over-under baffles for channeling flow through the unit. A computational fluid dynamic (CFD) analysis of flow through this vessel reveals that the well intentioned baffles in fact generate high velocity flow paths that allow water to bypass a significant fraction of the vessel's volume.

The distribution of gas bubbles in a flotation cell is equally critical for efficient water cleaning. Again, CFD analysis can be used to validate the design of eductor geometry to insure that bubbles are well distributed within a flotation vessel. Figure 2 shows how the use of an eductor that distributes gas bubbles in a horizontal, radial pattern can distribute gas bubbles over an area that exceeds a 6 ft diameter circle. Figure 3 then shows how the use of multiple eductors in a 10 ft diameter vessel effectively distributes gas bubbles over the entire cross sectional area of a compact column flotation cell.

Gas Bubble Size. A parameter can be defined which is related to the efficiency of gas flotation. The parameter is the "Sweep Factor" [1]. The Sweep Factor defines the number of times per minute that a given volume of a flotation cell is swept by a rising gas bubble. As the Sweep Factor increases, so does the number of contaminant-bubble interactions. The higher the bubble-contaminant interaction frequency, the greater the probability is that flotation will perform satisfactorily. The Sweep Factor for a flotation cell is calculated as follows:

$$\text{Sweep Factor (min}^{-1}) = (A_{gas} \times F_{gas})/A_{cell}$$

Where

A_{cell} = cross sectional area of flotation cell (ft^2)

F_{gas} = gas flow rate (ft^3/min)

A_{gas} = total cross sectional area of gas bubbles per unit volume (ft^2/ft^3)

If flotation gas is injected into a unit at the rate of 1 ACF/BBL of produced water, then the Sweep Factor as a function of bubble diameter is as follows:

Bubble Diameter (microns)	Sweep Factor (min^{-1})
100	1634
120	1362
200	817
300	545
400	408

Although smaller bubbles will be more effective for flotation, vessel hydraulics will limit the actual size of bubbles that can be used for flotation. In compact column flotation, for example, a typical design parameter is the nominal downward velocity for water in the unit. Figure 4 shows the rise velocity of gas bubbles, oil droplets, and oil droplets associated with a gas bubble of the same diameter. To overcome a 2 ft/min nominal downward water velocity, an oil droplet would need to have a diameter $\geq$300 microns, a gas bubble would need a diameter $\geq$120 microns, and an oil droplet associated with a gas bubble would need an effective hydraulic diameter in excess of 155 microns. Thus the lower limit for gas bubble diameter during the practical application of column flotation is in the range of 120 to 150 microns.

Contaminant Size. As illustrated in Figure 4, flotation becomes more efficient as the size of the contaminant increases. For compact flotation systems, it is particularly important that oil droplet size be increased as much as possible by mechanical and chemical means. The effective size of oily solids and/or chemically stabilized oil droplets must be increased by the use of an appropriately selected chemical flocculent for flotation to be effective.

For compact column flotation, two simple mechanical means are available to assist with oil droplet growth. The first is a cyclonic inlet, Figure 5, that subjects the incoming water to 15 – 30 G's of force. Under these conditions oil droplets migrate to the center of the inlet device where coalescence is enhanced. The second means is the installation of high surface to volume ratio packing, Figure 6. By utilizing an open structure, random packing without long contiguous surfaces, droplets have a opportunity to encounter a coalescing surface, but clogging by solids is minimized. In the Gulf of Mexico, the random packing shown in Figure 6 has been in service for two years without clogging.

Applying Flotation Principles to Compact Single Cell Flotation Vessel Design

On floating platforms, space restrictions and the consequences of water sloshing within vessels are forcing designers to specify compact column flotation for their water treatment facilities. The vessels for this service must be carefully designed because they are generally restricted to one, or at most, two stages of flotation. Since fewer stages of flotation can impact water treatment performance, additional attention must be given to the process design around the water treatment facilities.

Inlet Design. For compact flotation, the cyclonic inlet has particular advantages. As described above, this type of inlet acts as an oil droplet coalescer. In addition, the cyclonic inlet releases gas slugs from the incoming water so that they will not disturb the layer of floating contaminants (oil and solid) on the surface of the cell while retaining smaller gas bubbles in the water that can provide the 1st stage of flotation in the upper section of the vessel. As an example, produced water discharged from a separator operating at 150 PSIG may release as much as 1.5 SCF of gas per barrel (5.6 ft^3) of water.[3,4] Thus fluid arriving at the IGF may have a gas volume fraction in excess of 20%. If this gas is present as small bubbles (e.g., <500 microns), it can be beneficial for effecting flotation. However, if the gas bubbles are large, then they can disrupt oil skimming. Thus the cyclonic inlet shown in Figure 5 is designed to make this kind of gas-liquid separation. Water is then released radially from the inlet at which point it is spread over the full cross section of the column flotation unit.

Flotation Stages. A compact column flotation vessel can be configured to provide essentially two stages of flotation in a single vessel. The first stage of flotation takes place in the upper part of the vessel and depends upon the breakout of dissolved gas in the feed water for effecting flotation. As discussed above, the smaller bubbles of breakout gas are used for this purpose while larger bubbles and gas slugs must be diverted from the liquid phase to avoid disruption of flotation and contaminant skimming.

To maximize the time for gas bubble and contaminant interaction, flotation gas is introduced near the bottom water outlet of the vessel. The introduction of dispersed gas bubbles instead of dissolved gas breakout bubbles is preferred at this location as the latter tend to be very small, sometimes under 10 microns diameter.[5] As discussed above, bubbles this small will be unable rise in the vessel and instead will be carried to the produced water outlet. Another consideration with respect to dissolved gas flotation is that very high gas pressures are needed to dissolve sufficient gas in the produced water to effect good flotation. For example, if 25% of the clean produced water is recycled to the dissolved gas system, then, based upon published gas solubility data, a pressure of about 500 PSIG would be required to dissolve sufficient gas in the water to provide 1 SCF of gas bubbles per barrel of flotation cell capacity.

Gas Bubble Generation and Distribution. Based upon CFD simulations, a radial discharge eductor was developed[6] that distributes 150 micron gas bubbles uniformly over a substantial cross sectional area of the column flotation cell. The dispersion of gas bubbles by this eductor is illustrated in Figure 2. By using multiple eductors, a uniform distribution of gas bubbles can be generated for any size of compact column flotation cell. The bubble size generated by this eductor is in line with the design parameter of 2 ft/min. for the nominal downward water velocity in the cell. It should be noted that although vessel designs allowing smaller gas bubbles are possible, the increased size of these units erodes their space-saving and cost-reducing character.

Clean Water Discharge. As with the inlet, the outlet of the flotation cell must also be carefully designed. For column flotation, some means of insuring that flow from the full cross section of the vessel is drawn uniformly to the outlet. If this is not the case, the influence of the high flow velocity to the outlet will extend up the length of the flotation cell, generating short circuit paths that allow rising gas bubbles and down-flowing produced water to by-pass each other. The result would be a reduced actual residence time for water in the cell and less effective flotation. For compact column flotation, the outlet nozzle is baffled to generate a dispersed flow of water to the point of discharge.

Removing Contaminants by Skimming from a Compact Flotation Cell on a Floating Platform. The configuration of compact column flotation vessels is particularly well suited for installation on floating platforms such as spars and FPSO's. On floating platforms, the water in any vessel will experience significant sloshing. Previous studies on the control of slosh motion provides[7] guidance for the design of skim systems for compact column flotation. CFD simulations were used to guide the development of a 2-stage skim bucket design for column flotation. This system, illustrated in Figure 7, allows water and oily contaminants to spill over into a set of shallow buckets near the center of the vessel. These shallow buckets have holes that allow water to return to the main part of the cell but retain floating oily contaminants. The retained contaminants then skim over into an oil bucket for discharge. By using this 2-stage skimming concept, the total volume of fluid skimmed from the compact flotation vessel can be minimized (typically 3 – 5% of design capacity) and the oil content of the skim liquid is maximized.

Process Considerations for Successful Water Treatment

Several factors in a separation process train can affect the successful performance of a water treatment system in general and the performance of an induced gas flotation (IGF) vessel in particular. Two factors that are particularly important are the avoidance of contaminant recycle streams within the separation process, and the selection of proper locations for chemical injection.

Avoiding Recycle Streams. To illustrate the potentially negative impact of recycling the reject streams from hydrocyclones and the skim liquids from a flotation cell, considering the following example from a North Sea platform. Performance data from on-board sampling showed that with a skim rate of 5%, the IGF was removing about 90% of the solids from 120,000 BPD of produced water. The solids content of the water entering the separation train from the wellbay header was approximately 50 PPM. However, the solids content of the water entering the IGF was just over 100 PPM. The skim liquids from the IGF were recycled to the production separator after an intermediate stop in a slop tank which had no oil/water separation capability.

By setting up a spreadsheet with the iterative calculation feature activated, one could follow the material balance of solids through the system. To reproduce the solids-in-water data, the calculation showed that 60% of the solids captured in the IGF were returned to the produced water via the production separator. These (oil coated) solids negatively impacted the performance of the IGF and resulted in reduced discharge water quality. Since the water was disposed of via injection, the presence of excess oily solids in the discharge water was viewed as a matter worthy of some concern.

It should be noted that the same consideration for avoiding recycle applies to hydrocyclone reject streams as well. Field data indicates that these streams can contain a significant concentration of sub-10 micron, oil-wetted solids, typically scale mineral precipitates, which if recycled, will degrade discharge water quality and increase chemical treating requirements.

The problems associated with the recycling of contaminants can be largely avoided by sending the skim liquids from an IGF and the reject stream from hydrocyclones to a small separator (reject accumulator). In total, the volume of this stream will be between 5 and 10% of the produced water treating capacity. In the reject accumulator, a solids and chemical laden oil layer will develop that typically contains 25 to 50% water. However, the actual volume of water in this reject emulsion is quite small. Thus the contaminated emulsion can be sent directly to a sales oil line with minimal impact on the oil's BS&W.

Consider, for example the 120,000 BWPD system discussed above. The water discharged from the production separator typically contained <300 PPM of oil. Thus the water treatment system would have an opportunity to capture about 36 BOPD, in this case, it was determined, with 25% BS&W. By sending this emulsion directly to the production sales line, only 12 BWPD were being injected into the sales oil, increasing the BS&W of the sales oil by less than 0.1%.

Locating Chemical Injection. Water clarifier chemicals are by their nature surfact active. Thus any chemical injected into a produced water stream will quickly associate itself with oil droplets and exit the produced water stream along with the contaminants at the first opportunity. Thus, for example, a clarifier injected upstream of a hydrocyclone or a degassing tank will provide no assistance to IGF performance. To assist the performance of an IGF, the flotation aid must be injected at a location upstream of the IGF with no other process vessels between the injection point and the IGF.

Compact Single Cell Column Flotation Vessel Design and Performance

A schematic illustration for the VersaFlo™ single cell column flotation vessel[8] that incorporates the design features discussed above is shown in Figure 8. As shown, the 60" diameter vessel has a rated capacity of 10,000 BWPD and has been operating on a spar in the Gulf of Mexico for over two years with, to date, no maintenance required. Several additional units with design capacities between 40,000 and 70,000 BWPD are either installed or under construction.

Produced water enters the unit through the cyclonic inlet and is spread horizontally over the full cross section of the vessel. The 1st stage of flotation utilizes gas that is breaking out of solution as a result of the pressure drop from the upstream separator to the IGF. The partially cleaned water flows down through the coalescing pack into the lower flotation chamber where gas bubbles are introduced and distributed over the full cross section of the vessel by the radial eductor. The total residence time from the bottom of the cyclonic inlet to the level of the radial eductor is about 4 minutes. A baffle plate is installed over the bottom water discharge nozzle to distribute the flow to the discharge nozzle from as wide an area as possible. In some cases, additional means of insuring this flow distribution may be required.

To assist with the introduction of polymer flocculents, the unit is equipped with a commercially available venturi injector. The polymer is injected first into a small side stream from the eductor recycle pump where it becomes fully hydrated and diluted before being mixed with the inlet water stream. As a result of this pre-hydration, the polymer acts quickly to flocculate oil droplets and oily solids without the formation of polymer globules or depositing on surfaces within the vessel.

Performance data for the VersaFlo™ column flotation unit illustrated in Figure 8 is shown in Table 1.

Summary and Conclusions

The design of single cell, compact column flotation units requires a good understanding of the vessel hydraulics and the need to maximize the interactions between gas bubbles and oily contaminants. The inlet to the vessel should allow breakout gas bubbles to contribute to the first stage of flotation while preventing large gas bubbles from disrupting the oily skim layer on top of the vessel. Flotation performance is assisted by equipping the vessel with two mechanical means for coalescing oil droplets and encouraging flocc growth. Gas bubble and oily contaminant interaction is maximized by uniformly distributing produced water from the inlet and gas bubbles from the radial eductor across the full cross section of the vessel. Operating performance has been excellent for over two years with no maintenance requirements.

Acknowledgments

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Nomenclature

V = velocity (ft/min)

A = cross sectional area (ft^2)

F = gas flow rate (ft^3/min)

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SI Metric Conversion Factors

in	x 2.54	E-02	=	m
ft	x 3.048	E-01	=	m
ft^2	x 9.29	E-02	=	m^2
ft^3	x 2.83	E-02	=	m^3
bbls	x 1.59	E-01	=	m^3

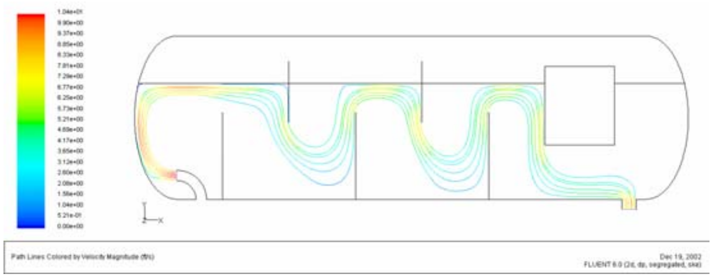

Fig. 1—A two-dimensional Computational Fluid Dynamic simulation of flow patterns in a horizontal vessel illustrates how baffling can generate high velocity fluid-flow paths.

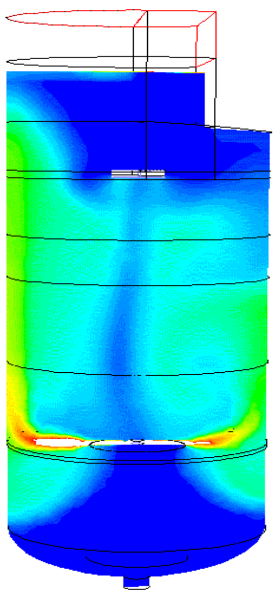

Fig. 2. By using a radial distribution pattern, gas bubbles can be distributed over a large area in a column flotation cell. The eductor geometry controls the gas distribution area.

Fig. 3. Four radial eductors distribute flotation bubbles over the cross sectional area of a 10 ft. diameter VersaFlo^{TM}. The water discharge end of the cyclonic inlet is also visible.

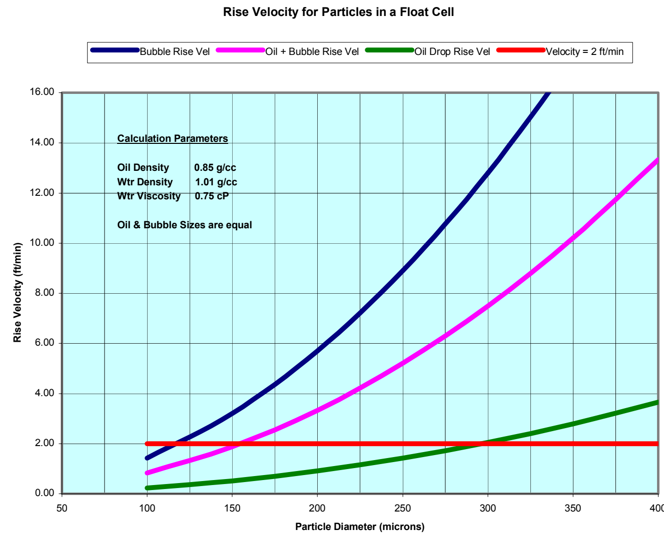

Fig. 4. Calculated rise velocities are shown for gas bubbles, oil droplets, and oil droplets with associated gas bubbles. The minimum bubble size for rising against a 2 ft/min. downward water flow velocity is about 120 micrcons.

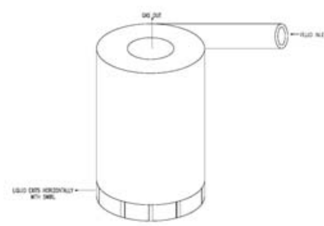

Fig. 5. The cyclonic inlet used for a compact column flotation vessel is shown. Gas exists the top of the cyclinder, liquid is radially distributed from the bottom, see Fig. 3.

Fig. 6. A high surface to volume ratio packing without large contiguous surface area is installed in a 10 ft. diameter compact flotation vessel. Packing has been in service for over two years without plugging.

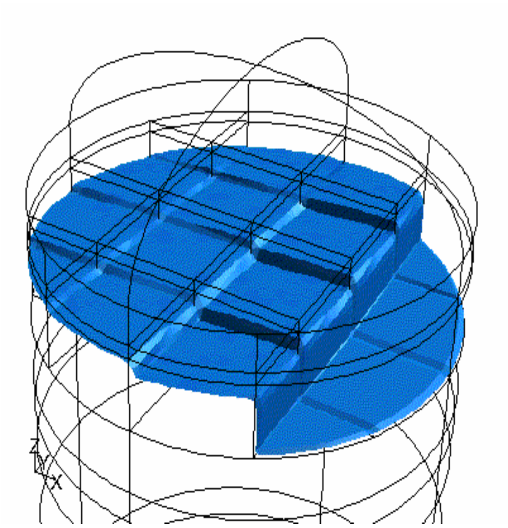

Fig. 7. A 2-stage skimming arrangement is used in the vertical column flotation unit to control skimming when liquid is sloshing due to vessel movement on a floating platform.

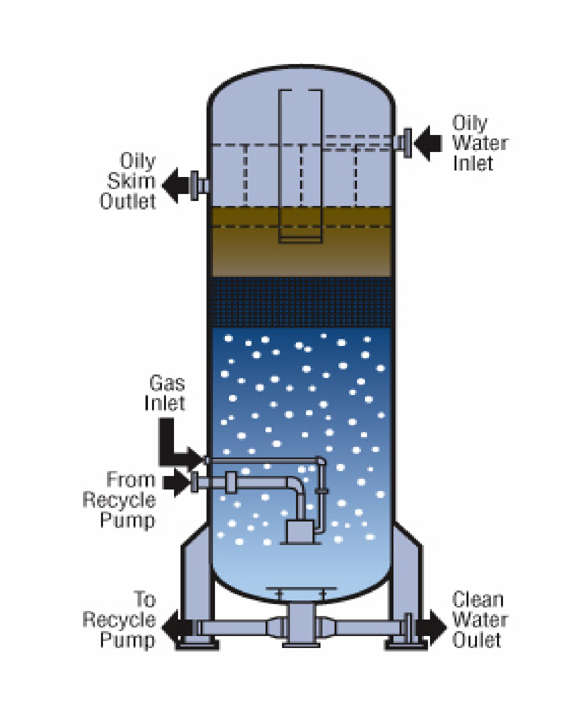

Fig. 8. A schematic illustration of a compact, single cell flotation vessel (US and Foreign patents pending) that incorporates the key design features for the practice of efficient flotation on a floating platform.

Date	Inlet TOG	Outlet TOG
02-03	52 mg/liter	27 mg/liter
02-03	48	19
02-03	37	13
10-03	47	15
10-03	55	23
01-04		12
02-04		14
03-04		6
04-04		20
06-04		12
07-04		19
08-04		12
09-04		14
10-04		Hurricane Ivan
11-04		low water flow
12-04		13

TOG: Total Oil & Grease as measured by EPA 1664

Table 1. Oil-in-water data are shown for produced water downstream of a VersaFlo^{TM} column flotation unit installed on a spar in the Gulf of Mexico. Water discharges to the flotation unit through a deoiling hydrocyclone.