NOVEL VERTICAL COLUMN FLOTATION DESIGN FOR GULF OF MEXICO DEEPWATER FLOATING STRUCTURES

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I. Introduction And Background

Oilfield operating companies in the Gulf of Mexico (GoM) continue moving to ever-increasing water depths to produce oil and gas reserves. Producing in these deep water locations has caused a shift from the traditional fixed-leg platforms to floating structures – various types of tension-leg platforms (TLP), SPAR platforms and other emerging technologies. For processing equipment technologists and designers, this shift to floating structures has created challenges. For example, due to the high cost to construct floating platforms, it is imperative that the size and weight of processing equipment be kept as low as possible. In addition, fluid processing equipment that is installed on the topsides of these floating structures is subject to more severe wave-induced motions. These issues must be taken into consideration when designing topsides equipment in order to minimize any adverse impacts to capacity and performance. In recent years, deepwater GoM operators have adopted a trend toward the use of liquid-liquid hydrocyclones followed by vertical column flotation units to treat produced water prior to overboard disposal since this type of solution results in a smaller, lighter system design. This paper focuses on the use of vertical column flotation equipment in GoM deepwater operations. After giving a brief description of the flotation process, the paper discusses the product development of a novel vertical flotation column, known as VersaFlo^{TM} (Patent Pending) that is designed for operation in deepwater fields. Each design feature of this new product is described in terms of how flotation performance is improved. Next, the results of a full-scale field implementation are reported.

II. Description Of Vertical Column Flotation

Column flotation units use a vertically oriented cylindrical vessel to contain the produced water for treatment. The produced water often enters the vessel near the top and flows downward. Simultaneously, gas bubbles are introduced to the vessel near the bottom and float upward. The primary objective of flotation is to populate a produced water stream containing oily contaminants (dispersed oil droplets and/or oil-coated solids) with gas bubbles such that as the bubbles rise to the surface. As the bubbles rise, they collide with, cling to, drag along, and float the oily contaminants to the surface. Once at the surface, the contaminants are skimmed off and removed from the vessel. Clean produced water exits from the bottom of the vessel beneath the gas entry point. Bubble formation and bubble distribution can be achieved by using a properly designed eductor that uses recycled clean produced water as the motive liquid. When clean produced water is pumped through an eductor, a low pressure zone is created in the eductor. Gas from the top of the vessel is routed to the eductor through a small diameter tube. Gas is pulled into the eductor by the vacuum and mixed with the water prior to entering the vessel. This gas/water mixture is used to introduce the bubbles needed for the flotation process. Gas bubbles that disengage at the gas-liquid interface exit the vessel via the gas outlet or are recycled to the bottom of the vessel for flotation. See Figure 1. Oftentimes it is necessary to inject a chemical agent to promote bubble-contaminant interaction. Many times these chemicals are long-chain polymers that impart an electrical charge to the oily contaminants or render them hydrophobic. This phenomenon increases the possibility that the contaminants will cling to the bubbles and float to the surface.

Based on the foregoing description, it can be concluded that the primary factors affecting the performance of a flotation unit are:

- Quantity of gas bubbles formed
- Size of gas bubbles formed
- Proper distribution of gas bubbles across the vessel cross-sectional area
- Proper distribution of produced water across the vessel cross-sectional area
- Downward velocity (flux) of the produced water
- Proper water chemistry to promote bubble-contaminant interaction
- Particle size of the contaminants

III. VERSAFLO™ PRODUCT DEVELOPMENT

As noted above, the use of floating platforms in deepwater GoM operations has led to many challenges for oilfield equipment technologists and designers. Some of the primary issues to be addressed by equipment designers are:

- Wave-induced motion
- Compact size
- Reduced weight

A team of NATCO Group water treatment experts was assembled to re-design column flotation to make it more suitable for operation in deepwater GoM operations. The team agreed that a vertically mounted cylindrical vessel is optimal for compactness. Furthermore, when compared to the horizontally oriented four-cell flotation device, the vertically oriented single-cell design also provides a significant reduction in weight.

However, the oil removal efficiency of the one-cell vertical column flotation unit is a major concern due to the fact that the produced water makes only one pass through the unit (versus the four stages of removal afforded by the horizontal unit). Realizing this point, the team felt they must ensure peak efficiency from the vertical flotation column. Hence, attention was given to addressing all the primary factors affecting flotation performance, as mentioned in Section II above.

After reviewing the designs for commercially available vertical column flotation technology, the team went “back to the drawing board” to begin developing design improvements. As a starting point, computational fluid dynamics (CFD) was used to model vertical column flotation systems. Various parameters were studied to understand their effect on the overall flotation process. For example, the CFD analysis showed that the use of a header-and-lateral inlet device caused produced water short-circuit paths inside the vessel. Surprisingly, the CFD model predicted that the produced water from the header-and-laterals inlet is directed to the vessel wall and from there continues on a path down the vessel wall to the water outlet. As has been stated earlier, for effective vertical column flotation, it is necessary to have proper distribution of the produced water over the full cross-sectional area of the vessel.

The CFD analysis also illustrated how the produced water downward velocity, or flux, is an important factor to consider in determining the average size oil droplet, solid particle or gas bubble that will float to the surface. This finding is no more than a basic application of Stoke's Law for a rising or falling spherical object through a viscous fluid. The fact that the oily contaminants are rising in a countercurrent fashion against the down-coming produced water stream means that as the produced water flow rate increases, the drag force on the oily contaminants also increases. As the downward drag force increases, there is a greater tendency for the oily contaminants to exit the bottom of the vessel along with the produced water. Figure 2 shows that for any given flux rate, there is a minimum oil droplet size that will rise to the surface in the flotation vessel. If the produced water flux exceeds this value, then the oil droplets will be carried along with the produced water to the clean water outlet. This same logic applies to gas bubbles and gas-contaminant conjoined particles. Hence, the produced water downward velocity must be slowed sufficiently to allow the oily contaminants to rise to the surface. Another conclusion that can be drawn is the fact that the gas bubbles generated for the flotation process must be large enough to allow a reasonable gas flux in the vessel. The VersaFlo™ design team set as a goal to achieve a practical range for the water and gas flux rates. The gas flux is interpreted by defining a parameter that is referred to as the "Sweep Factor". This number defines how many times per minute gas bubbles will contact any particular volume element in the flotation cell.

In terms of wave-induced motion effects, the CFD output showed severe turbulence existing at the gas-liquid surface during storm conditions. It is obvious that under these storm conditions the amount of liquids, especially water, removed from the oil outlet would dramatically increase, resulting in extremely high recycle rates. In addition, the turbulence produced in the vessel would create high oil concentrations in the clean water outlet. Resolving this situation is usually accomplished by installing anti-motion baffles inside the vessel. As will be discussed later, CFD modeling was used to design an effective two-stage oil skimming system.

Perhaps the most important result of the CFD modeling work is related to the performance of the gas eductor. Most gas eductors in use on vertical column flotation cells are mounted outside of the vessel. As the produced water and gas mixture is created just downstream of the eductor, this mixture is routed inside and to the bottom portion of the vessel via a section of pipe. As the gas passes through this piece of pipe, however, the small gas bubbles formed in the eductor can collide, coalesce and form much larger gas bubbles before being released into the produced water. The effect of releasing the larger gas bubbles is that the bubbles tend to rise very quickly making it much more difficult to distribute the bubbles out over the full cross-sectional area of the vessel. The result is that a short-circuit path for the gas is formed up the center of the vessel from the eductor outlet to the liquid surface. It is obvious that this lack of good distribution of the gas bubbles across the entire cross-sectional area of the vessel adversely affects the performance of the flotation cell.

Since this finding has such a significant impact on the performance of the vertical flotation cell, the team decided to conduct physical laboratory tests to verify the CFD results. The test vessel measures 60"OD X 14' S/S. A conventional gas eductor used successfully in horizontal flotation cells was purchased and installed in the normal fashion inside the vessel. Figure 3 shows the fact that the gas bubbles entering the produced water are very large and that the bubbles are not well distributed due to the fact that the bubbles rise very quickly to the liquid surface. This is the same behavior as predicted by the CFD model. As will be discussed later, CFD modeling was used to correct this problem and provide an eductor with the ability to distribute the gas bubbles evenly over the cross-sectional area of the vessel.

To summarize, four critical issues were identified by the VersaFlo™ development team that must be addressed in the VersaFlo™ design. These issues are:

- Produced water short circuiting due to improper design of the inlet device
- Produced water downward velocity too high
- Wave-induced motion affecting oil removal
- Premature gas bubble coalescence with poor bubble distribution

The VersaFlo™ Team next set out to resolve these design issues.

IV. VERSAFLO™ DESIGN FEATURES FOR GULF OF MEXICO DEEPWATER FLOATING STRUCTURES

With an improved understanding of the design requirements for the vertical column flotation process, the VersaFlo™ team proceeded to incorporate their ideas into a novel vertical column flotation design more suitable for Gulf of Mexico deepwater floating structures. The following paragraphs summarize the major design features developed by the VersaFlo™ design team as the team addressed each of the problem areas previously mentioned in Section III.

* **Produced water short circuiting due to improper design of the inlet device**. A rigorous hydraulics study of the header-and-laterals style inlet using CFD analysis revealed that this inlet design promotes severe produced water short circuiting inside the vessel. To combat this situation, the VersaFlo™ design team incorporated a cyclonic inlet device. Three functions are performed by the cyclonic inlet that are beneficial for the VersaFlo™ operation.

First of all, as the fluids enter the VersaFlo^{TM} (Patent Pending) through the cyclonic inlet, gas bubbles larger than about 1 mm diameter are removed. These larger gas bubbles form as gas breaks out of solution due to pressure reductions across upstream separator control valves and/or hydrocyclones. If these bubbles are not removed, they can prove disruptive to oil skimming. Bubbles less than 1 mm are retained so that they can contribute to the 1st stage of flotation in the upper part of the VersaFlo^{TM}.

Secondly, the G-forces in the cyclonic inlet serve to pre-coalesce oil droplets in the contaminated water, improving subsequent flotation efficiency. As previously discussed, it is essential that optimal oil separation efficiency be achieved in the vertical flotation column since this device is essentially a one-pass unit.

And finally, the fluid exits the cyclonic inlet horizontally in a radial-swirl pattern to properly distribute the liquid over the full cross-section of the vessel. A CFD approach was used to compare the distribution characteristics of the header-and-laterals device versus the cyclonic inlet device. Dramatic improvement in produced water distribution can bee seen in the CFD characterization. Improved produced water distribution is crucial to the design of any vertical column flotation system due to the impact of this on oil separation efficiency.

* **Wave-induced motion affecting oil removal**. Attenuation of wave-induced motion, or sloshing, is a critical aspect of the design of vertical column flotation units on floating platforms. The VersaFlo^{TM} is equipped with a 2-stage skimming system to allow efficient oil-water skimming during vessel movement on a floating platform. Again, CFD was used to develop the skimming system. In the first stage, oil and water slosh into a pre-skim chamber from which water can egress through bottom holes, but oil is retained. This accumulated oil layer is then skimmed into a conventional oil bucket with a controlled amount of water carry-over.

* **Gas bubble coalescence by externally mounted eductor.** The proper distribution of gas bubbles over the entire cross-sectional area of the vessel is critical for optimizing the oil separation efficiency of the vertical column flotation unit. In addition to proper distribution of gas bubbles, the size of the bubbles induced into the produced water must meet certain criteria to promote good oil separation. With the aid of CFD studies, the VersaFlo^{TM} design team developed the Radial Eductor^{TM} (Patent Pending), a new concept in hydraulically induced gas injection. As previously discussed, many gas eductors used in vertical column flotation units are mounted externally and the gas-water mixture is routed inside and to the bottom of the vessel through a piece of pipe. While in the pipe, the small gas bubbles created by the eductor collide, coalesce and grow to be much larger at the point of entry into the produced water stream. The Radial Eductor^{TM} is mounted inside and near the bottom of the vessel. A separate gas line from the gas space of the vessel is routed to the Radial Eductor^{TM} inlet. As the gas-water mixture is created in the Radial Eductor^{TM}, the mixture is immediately released into the produced water stream. The result of this approach is that the gas bubbles created by the Radial Eductor^{TM} remain

small and are more easily distributed across the entire cross-sectional area of the vessel. See Figures 4 and 5.
The geometry of the Radial Eductor^{TM} can generate a spread of gas bubbles uniformly over a 5 – 7 ft diameter circular pattern. For large size vessels, multiple eductors are used to insure a uniform distribution of gas over the entire cross section of the flotation cell.

* **Produced water downward velocity**. The sizing of a vertical column flotation cell is a compromise between vessel cost/weight, and the need to maintain a relatively slow downward water velocity. The higher the downward water flux, the larger that oil droplets and gas bubbles must be in order to rise against the downward flow. Early field experience with column flotation showed that a downward flux of 4 ft/min. was too high for effective flotation. For VersaFlo^{TM}, a net downward water flux of 2 ft/min was selected as an optimum design parameter. Figure 2 shows the limiting rise velocities in produced water at about 110 ^{o}F as a function of diameter for gas bubbles, oil droplets, and gas bubbles attached to oil droplets. These values were calculated using Stokes Law. Note that a gas bubble size greater than 120 microns is required to achieve a rise velocity > 2 ft/min. Using a sophisticated video-microscope-stroboscope system, bubble sizes from the Radial Eductor^{TM} (Patent Pending) were determined to have a narrow size distribution with a median near 150 microns. An oil droplet with an equal sized gas bubble attached to it must have a diameter larger than about 150 microns to achieve a rise velocity > 2 ft/min. Water clarifiers and flocculants are widely used with great success to generate particles this large from oil droplets as small as 4 – 5 microns and allow them to be removed via flotation in 4-cell horizontal and in 1-cell vertical units.

* **Other features of VersaFlo^{TM}**. The VersaFlo^{TM} unit may be equipped with an optional coalescing media section. If required, the coalescing media, which has a very low solids plugging tendency, is installed in the vessel beneath the cyclonic inlet device. See Figure 6. Another feature of the VersaFlo^{TM} unit is the specially baffled produced water outlet. The purpose of the baffled design is to prevent short-circuiting of water from the center of the cell. The VersaFlo^{TM} is also equipped with a Mazzei venture eductor for the easy introduction of high molecular weight polymer flocculants into the feed water. These flocculants are difficult to fully hydrate and disperse conventionally. However, the use of the Mazzei venturi eductor overcomes this dispersion difficulty and allows the use of high molecular weight polymers for the flocculation and flotation of oily solids.

V. FIELD TRIAL RESULTS

The first commercial size field trial of the VersaFlo^{TM} came in November 2002. At that time, a 10,000 BWPD VersaFlo^{TM} unit was installed in the GoM on a SPAR platform. The platform operator was having difficulty meeting the government regulation for overboard water quality and needed a quick, efficient solution. NATCO offered the VersaFlo^{TM}. After a one-month construction period, the VersaFlo^{TM} unit was installed on the platform. See Figure 7. Once installed, a

NATCO technician was sent to the field to commission the unit. During the commissioning phase, the NATCO personnel recommended several ways that the operator could improve the overall water treatment system, and these recommendations were also implemented.

NATCO personnel also performed chemical screening and optimization tests. As a result, chemicals were selected that gave good performance with low consumption. Oil and grease measurements were performed using a Wilk's Infracal^{TM} IR oil-in-water analyzer. This unit was chosen due to the high concentration of methanol in the produced water and also as a means of using an IR method to mimic a gravimetric result.

Table 1 summarizes several oil and grease test results from the produced water effluent of the VersaFlo^{TM} unit. As this table indicates, the VersaFlo^{TM} unit is operating well below the federal limit for liquid discharges into the sea. As of the time of this writing, the VersaFlo^{TM} unit has been operational for nearly one year and there have been no operational problems or non-compliance events associated with this unit. In fact, the operator has been able to cease injection of one of the two chemicals, thus allowing a reduction in OPEX.

VI. CONCLUSION AND FUTURE WORK

Vertical column gas flotation is an effective means of produced water treatment for deepwater GoM operations. A vertically oriented flotation vessel offers significant weight and space reduction which is vital on TLP and SPAR platforms. Due to the more pronounced wave-induced motions on TLP and SPAR platforms, the vertical column flotation system must be properly designed to achieve high oil separation efficiency. This is especially so since the vertical column flotation design is a one-pass system.

Computational fluid dynamics (CFD) is a powerful diagnostics and design tool that allows equipment designers to be more creative. The VersaFlo^{TM} design team used CFD analysis not only to uncover the existing design flaws but also to develop new designs to improve flotation performance.

Thus far the new VersaFlo^{TM} (Patent Pending) system design has performed well. In fact, the operating company has benefited from the reduced chemical requirements of the VersaFlo^{TM} unit (reduced OPEX).

VersaFlo^{TM} technology has been installed on another GoM SPAR platform that is due for commissioning later in 2004. Other operating companies in the GoM and in other deepwater regions have also shown an interest in applying the VersaFlo^{TM} design in their produced water treatment systems. As feedback from existing and new field installations is received, additional enhancements will be made to the VersaFlo^{TM} design.

LIST OF FIGURES

FIGURE 1. VERSAFLO^{TM} VERTICAL COLUMN FLOTATION UNIT SCHEMATIC

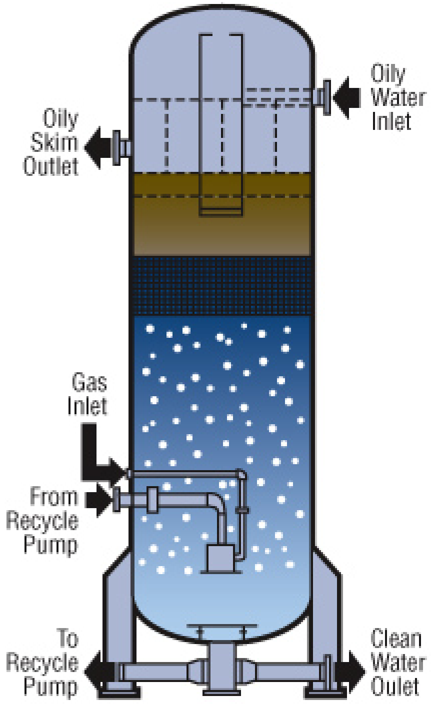

FIGURE 2. RISE VELOCITY FOR PARTICLES IN A FLOTATION CELL

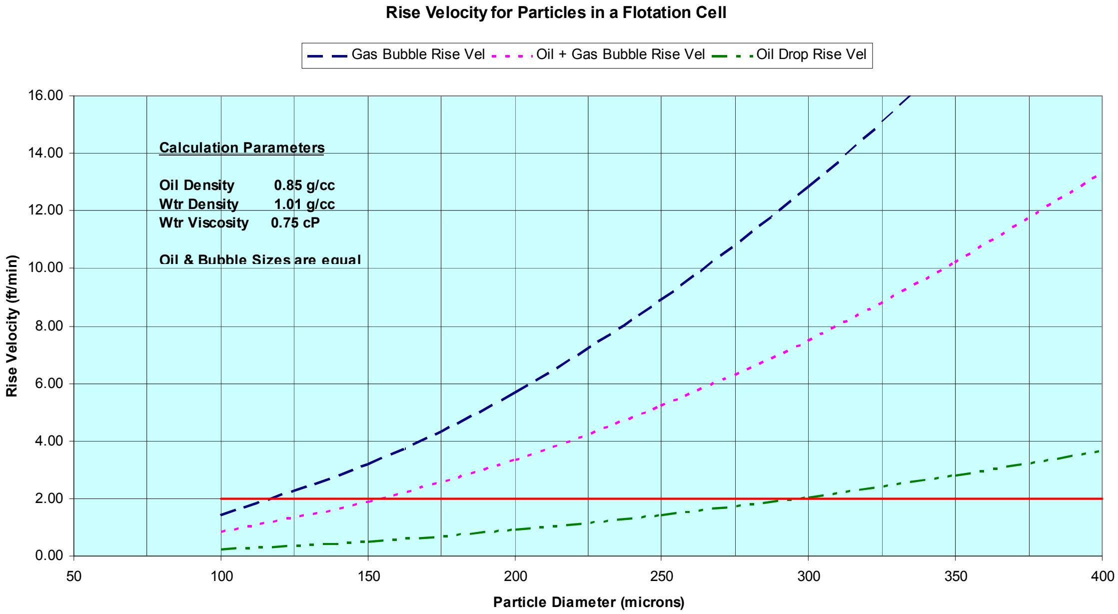

FIGURE 3. GAS BUBBLE SHORT CIRCUITING WITH CONVENTIONAL EDUCTOR

FIGURE 4. RADIAL EDUCTOR™ DISTRIBUTION PATTERN

FIGURE 5. RADIAL EDUCTOR™ BEING TESTED

FIGURE 6. VERSAFLO™ COALESCING MEDIA

FIGURE 7. 10,000 BPD VERSAFLO™ UNIT FOR DEEPWATER GoM INSTALLATION

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TABLE 1. VERSAFLO™ PERFORMANCE DATA

Date	**VersaFlo Inlet Oil Content (ppm)**	**VersaFlo Outlet Oil Content (ppm)**	**Produced Water Flow Rate (BPD)**	Sea State
02-07-2003	52	27	7000	**8'**
02-07-2003	48	19	6500	**8'**
02-07-2003	37	13	7000	**10**
02-08-2003	35	13	5500	**8'**
10-04-2003	47	15	6800	**5'**
10-07-2003	**55**	**23**	**7000**	**5'**