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Optimizing a Large-Vessel Separator Design for FPSO Operation in Bohai Bay

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Abstract

Designing separation equipment to be placed on an FPSO in Bohai Bay generates a unique set of obstacles that must be overcome. The large capacity of vessels designed for this area, producing low API oils, and the motion of the FPSO due to the local sea states can generate significant process fluid motion inside a separator. Bohai Bay has short wave motion periods which make interface control in a separator challenging. Any fluid motion within the separator can damage the process or the vessel structure if not appropriately contained. Several key separator components, when properly arranged, can control the fluid motions in a large Bohai Bay separator.

These key items will be analyzed and compared to yield a process vessel design with a reasonably quiet fluid interface. Wave amplitude and frequency must be determined for any interface within the vessel. Optimizing the vessel components that are used to control interface waves for the appropriate fill levels will manage the amplitude and frequency.

Wave amplitude can be reduced by dampening and compartmentalizing the fluid within the vessel. This is accomplished by balancing the placement of baffles for flow distribution with baffles for compartmentalization, which adjust the natural frequency.

The amplitude of interface waves generated inside a bare separator will be compared to the relatively quiet interface in a separator that has been designed using the above criteria. A properly designed separator will have an operating range extended into more severe sea states than a bare vessel can handle.

Introduction

The design of oil/water separators intended for installation on FPSO facilities has been the subject of many papers and conferences since the first FPSO was installed. Prior to the design of any FPSO production vessel, the designer must develop a thorough understanding of the vessel purpose, operating philosophy and survival conditions. The needs of the design can be summarized in three broad categories: performance, survival and installed cost.

Separators pose a particularly difficult challenge. They function with a liquid/gas interface that must be properly quieted to sustain performance without introducing too many internal components, which can reduce performance by re-mixing phases.

While the primary function of the separator is to achieve adequate phase separation during mild to moderate sea conditions, it is not and cannot be the only goal. The secondary function of a design must be to ensure vessel and component survival during severe sea states. Rice points out that FPSO separator designs must ensure process quality specifications and maximize on-stream time. As FPSO vessels move into deeper waters and more severe seas, separator designs must be optimized to maintain process performance while protecting the internals from damage.[1]

Costs

Capital expenses (CAPEX) and operating expenses (OPEX) are certainly considerations that must be properly weighed when making equipment selections. FPSO separators will undoubtedly have high CAPEX resulting from more engineering involvement, robust structural requirements, sophisticated level controls and significant vessel internals. Cost reduction measures such as standard vessel designs with minimum fluid-control internals can mitigate some of these increased costs.

OPEX for FPSO equipment can also be reduced (sometimes resulting in higher CAPEX) by first developing a sound operating philosophy related to the FPSO facility. For example, designing a separator to remain at normal operating levels at all times removes the requirement to be drained prior to a severe storm. Alternatively, filling prior to a storm will eliminate the liquid/gas interface within the vessel, which nearly eliminates interface-induced forces. These philosophical decisions can significantly reduce the OPEX associated with the equipment.

FPSO Operating Philosophy

While anticipated production rates, flow surges, stoppages and turn-around are a part of the operating philosophy for the FPSO facility, the separator designer is also concerned with the severe-weather operating philosophy, where equipment survival is their primary concern.

Three options are typically available to the operator. A process shut-in, which isolates fluids in the vessel at normal operating levels, is the simplest to implement, but provides significant design challenges related to interface sloshing and the induced forces.

The best protection is a complete drainage of the process fluids, which eliminates interface forces entirely. However, production demands generally delay draining until it is too late resulting in internal damage. In other cases, filling is started too soon, while seas are still turbulent following a storm, with the same results.

The most useful option is to flood the vessel with liquid and eliminate the liquid/gas interface entirely. This technique requires more structure to support a fluid packed vessel, but it also reduces the likelihood of damaging vessel internals during survival conditions.

Design

While performance, operating philosophy and costs are important considerations that must be understood and balanced in any separator selection, the FPSO separator design involves a wide range of objectives that the designer must meet. These objectives include:

Costs
- Installed cost
- Operating cost
- Installed weight

Performance
- Performance maintenance
- Interface controls
- Process controls

Vessel
- Internal configuration
- Internal survival
- Vessel survival

Expansion
- Installable options
- Process integration
- Redundancy

For dealing with the vessel internal configuration, Rice and Phenicie state that there are five general effects of motion on process equipment – spirit level effect, resonant waves, primary liquid turbulence, secondary liquid turbulence and process control effects. The goal of the FPSO separator design is to meet process performance requirements. However, stabilizing the spirit level by adding baffles to reduce the primary turbulence must be balanced with the necessary increase in secondary turbulence caused by the installation of compartmentalizing and dampening baffles.[2] Additionally, the process fluid must be permitted to flow from inlet to outlet while providing for effective oil / water / gas separation.

For the best optimization of a vessel design, the vessel would be modeled, either by CFD or by physical modeling. Frankiewicz and Lee have identified the necessity for this optimization of separator designs to meet the needs in FPSO applications. They state that, after proper validation, engineers are gaining confidence in CFD techniques to investigate a variety of vessel designs, rather than conducting expensive motion simulation studies. Not only can CFD results define the performance of separator internals, but it can also be utilized to investigate the placement of the separator on the FPSO facility.[3]

Standardization. While separator standardization cannot be fully implemented and cannot be justified in all cases, it does provide a sound basis for many designs. From a standardized design, internals can be added or removed as needed to meet the processing requirements. We believe a standardized design will have three basic components.

Inlet Zone. The inlet zone is an area near the front of the separator where the turbulence of the incoming fluids is contained, and the inlet momentum is absorbed. A low-porosity baffle is utilized to confine fluid near the head. If the inlet fluids contain a significant gas volume, then a cyclonic inlet device can be utilized to provide bulk two-phase separation. Because cyclonic devices are not as susceptible to vessel motion as other inlet devices are, they should be utilized whenever possible.

Several papers mention the use of cyclonic inlet devices to stabilize the inlet flow for maximum use of the separator. For first-stage separators where the gas flow is high enough to yield the necessary g-forces, this is recommended. However, three-phase separation, as will be demonstrated here, is often done in second-stage separators. In the second stage, the bulk of the gas has already been removed, and gas flow may be insufficient to induce the g-forces necessary for effective cyclonic performance. Therefore, for the example case, a cyclonic inlet has not been used.

Outlet Zone. Numerous studies have demonstrated that fluids will anticipate the outlet and travel the path of least resistance. In nearly all cases, this action results in a significant loss of effective retention time. To reduce this tendency, a low-porosity baffle can be utilized near the vessel outlets to maintain fluid distribution.

Quiescent Zone. The area between the inlet and outlet baffle defines the main separation zone where the required separation of fluids occurs. The efficiency of this zone can be optimized by including high-porosity dampening baffles as well as coalescing media.

Confidential studies have shown that perforated plate geometry plays an important role in reducing localized shear while optimizing distribution and dampening. Plate configuration includes hole pitch, size, geometry, porosity and plate thickness. These findings are not limited to FPSO application, but were found to be equally important in optimizing the performance of separators that have no imposed motion.

Natural Frequency Determinations

It has been shown that wave statistics follow a Rayleigh probability density function quite well.[4] This distribution function can be used to predict the probability that a wave of a particular amplitude will occur within “N” waves. While ocean waves can be represented by a Rayleigh distribution, more useful information can be obtained by studying the natural frequency and the vessel behavior subjected to that frequency.

As pointed out in NASA Report SP-106, there is no theory available for predicting the frequencies or a horizontal cylindrical vessel. Therefore, unlike rectangular vessels or vertical cylindrical vessels, the theoretical equation for calculating the natural frequency cannot be applied without correction.[5]

The NASA report presents a multiplying parameter to determine the natural frequency as a function of fill height for a cylindrical vessel with flat ends. From the data we obtained experimentally, a natural frequency parameter is calculated to produce equivalence in the following equation.

$$\lambda_n = \varpi_n \sqrt{\frac{\ell}{g \tanh(\frac{n \pi h}{\ell})}} \qquad (1)$$

Our experimental data for horizontal cylinders with flat ends fit closely with the NASA values. The NASA data, produced using vessel diameters from 5.5 to 12 inches and ranging in length from 16 to 24 inches, compared well with the data from our 24-inch diameter by 72-inch long vessel. For example, with a fill level at 0.5 times the diameter, the NASA report determined the natural frequency parameter to be 1.6. Our testing found the natural frequency parameter to be 1.68.

Another mathematical model has been presented utilizing a mass-spring-dashpot system to represent the fluid masses within a horizontal cylindrical vessel.[6] However, this model also failed to include the contribution introduced by the vessel heads. Our data indicates a significant variation in natural frequency and interface amplitude can be attributed to head type.

Since the vessel geometry affects the dynamics in a separator,[7] the natural frequency parameter must be experimentally determined for critical vessel geometries. It is beneficial to select conventional FPSO vessel designs for testing and evaluation, rather than rectangular vessels with flat ends. For example, using 2:1 elliptical heads and 0.5 fill fractions, we found the natural frequency parameter to be 1.35, and with hemispherical heads the parameter was found to be 1.36. Both these values indicate the natural frequency is reduced by about 10% when using heads.

Once the natural frequency parameter has been determined for a variety of head and baffle configurations, it is used as a multiplier to the theoretical natural frequency determined for fill height and compartment length. The theoretical natural frequency is calculated using Equation 2.

$$\varpi_n = \sqrt{\frac{g \pi \tanh(\frac{n \pi h}{\ell})}{\ell}} \qquad (2)$$

Since these experiments were conducted with a water / air interface, it is necessary to apply a correction factor to determine the natural frequency of the oil / water interface. Due to the smaller density difference between water and oil, the natural frequency is reduced significantly resulting in longer interface wave periods at the liquid / liquid interface. The ratio between the natural frequency of an oil-water interface and an oil-gas interface can be determined from the following damping factor.[6]

$$\gamma = \sqrt{\frac{(\rho_w - \rho_o)}{(\rho_w + \rho_o)}} \qquad (3)$$

Laboratory Testing

Bottomley suggests that one way to control the dynamics within a separator is to compartmentalize the separator to increase the interface natural frequency. He also points out that due to the complexity of the separator internals, an optimum design can only be defined by actual motion tests.[8] We submit that an optimum vessel configuration can be developed using experimental motion tests and then adapted as required to the needs of the process.

Test Description. Laboratory testing was conducted on a water-air system, using a cylindrical vessel 24” OD x 72” long made of transparent plastic to allow observation of the water motion in the vessel. Removable heads on the vessel allowed adding and adjusting the placement of baffle plates, as well as changing the head style. The water in the vessel was dyed to make the interface distinctive.

The vessel was placed on a wave-motion table to induce the required motions. A video camera attached to the wave table and wired to a monitor allowed close examination of the movement of the water-gas interface.

The base case for the series of tests used flat heads on the vessel, with no baffle plates, for comparison with the calculated data. The calculations found in the literature were performed with this configuration. Other arrangements included the use of hemispherical heads and 2:1 elliptical heads.

Baffle plates were installed in the vessel to test the ideas of compartmentalizing and dampening described by Bottomley.[8] For this test, three baffles with different porosities were used. The first baffle, Baffle A, had the lowest porosity. The porosity was in the range that the literature describes as being a compartmentalizing baffle, a baffle that divides the vessel into compartments that are harmonically distinct. Although baffles in this range allow fluid to move through them, they will behave harmonically as is they were solid walls.[5]

Brown states that baffles with a lower open area will mix the process fluids rather than aid in separation, due to higher velocities as the fluid moves through the holes in the baffle.[9] Therefore, Baffle B was added to the test setup. Baffle B had a higher porosity than Baffle A, but it was still in the porosity range for a compartmentalizing baffle.

A baffle that would dampen the amplitude of interface waves was also added to the test. Waldie and White have demonstrated that baffles with 22-53% porosity will fit into the dampening category. A 22% open area baffle will dampen the non-baffled wave by more than 80%, while a 53% open area baffle only achieves a 30% reduction.[10] The porosity of Baffle C fell within this dampening range, with a porosity just over twice that of Baffle A. There are some compartmentalizing effects with Baffle C, but it does not fully compartmentalize the vessel like Baffles A and B do.

All laboratory testing concentrated on vessel pitch rather than combined motions. Pitch was selected because it produces the most prominent interface movement for horizontal cylindrical vessels.

For each water level / baffle / head arrangement, the natural frequency and wave amplitude was obtained by conducting a series of tests for each configuration. This frequency and amplitude data was then used to determine the natural frequency parameter described in Equation 1. The following test configurations were analyzed:

- Comparison of heads: flat ends, 2:1 elliptical heads, and hemispherical heads
- Effect of baffle location in the vessel
- Comparison of the two compartmentalizing baffles, Baffle A and Baffle B
- Effect of adding Baffle C as a dampening baffle

Discussion of Results. The natural frequency and the wave amplitude were measured for each configuration, at water levels ranging from 25% to 80% of the vessel diameter. Data was generated by pitching the vessel +/-1.5^o over a range of frequencies. The results were then used to calculate the natural frequency parameter for each configuration, for extrapolation to full-sized vessel designs.

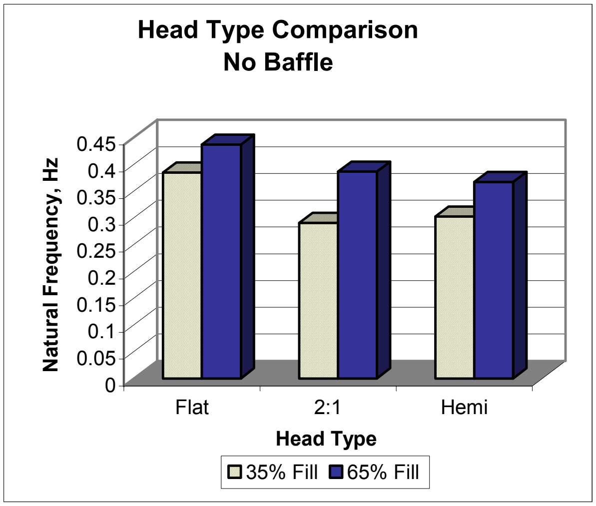

Figure 1

Head Analysis. Figure 1 compares the natural frequency of the test vessel with flat heads to the natural frequency with 2:1 elliptical heads or hemispherical heads, with no intermediary baffling.

As can be seen, there is a noticeable shift in the natural frequency from the flat heads to the curved heads. The difference in natural frequency between the flat heads and the curved heads demonstrates the difficulties in applying the natural frequency parameter without testing.

The difference in natural frequency between the two head types is not as significant. In this figure, the 2:1 elliptical head has a higher natural frequency than the hemispherical head for the 65% fill condition, but a lower natural frequency for the 35% fill condition. This would indicate a similar system response using either the elliptical heads or the hemispherical heads. However, observations made during the testing showed that, although the frequencies might be similar, the motion of the water in the vessel was more violent with the hemispherical heads than with the 2:1 elliptical heads.

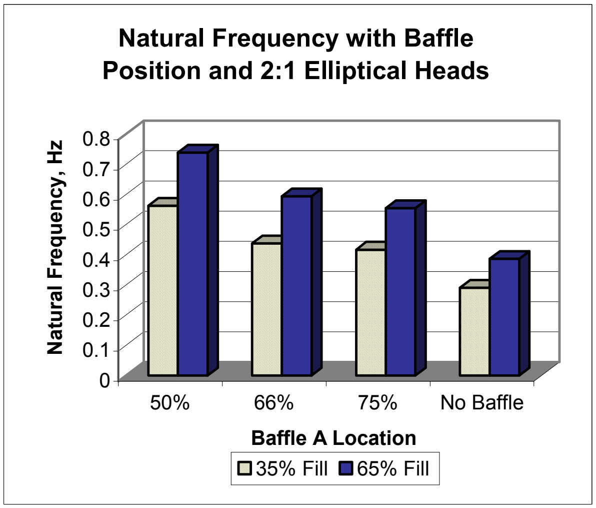

Figure 2

Baffle / Head Natural Frequency. Additional data that was required for the separator design for Bohai Bay is the effect of baffle location on the natural frequency of the vessel compartment. This effect is shown in Figure 2.

For this figure, Baffle A was placed at various percentages of the vessel length, seam-to-seam. The natural frequency was then measured on the longer compartment of the vessel created by the baffle placement. The shorter side was not included, because these natural frequencies are too high to measure amplitude accurately. By nature of the vessel, each compartment had a baffle at one end, and a head at the other end.

As is clearly shown for the baffle positions in Figure 2, the natural frequency steadily moves downward as the compartment length grows. This is to be expected from basic harmonic theory. However, the value of the natural frequency is different from what would be predicted using the theoretical natural frequency calculations. This is due to the effect of the 2:1 elliptical head, as was demonstrated in Figure 1.

Compartmentalizing Baffles. Baffles A & B have been described as compartmentalizing baffles. Figure 3 compares the natural frequency of the vessel with 2:1 elliptical heads and no baffle to the natural frequencies of the vessel with Baffle A or Baffle B installed at 66% of the vessel length (seam-to-seam). The natural frequency for the baffle cases was measured for the longer compartment created by the addition of the baffle, at fill levels of 35% and 65% of the vessel diameter.

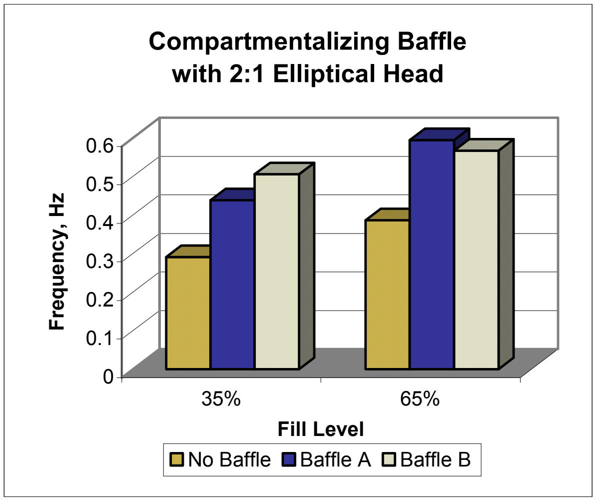

Figure 3

Both Baffle A and Baffle B do compartmentalize the vessel, drastically shifting the natural frequency. When compared to the natural frequency of the vessel with no baffle, the natural frequencies of the two baffle cases are fairly close. Baffle B has a higher natural frequency than Baffle A for the 35% fill level case, while the situation is reversed for the 65% fill level case.

As stated above, baffles with higher porosities will create less turbulence in the process fluid as it flows through the baffle. Since both Baffle A and Baffle B similarly compartmentalize the vessel, and Baffle B has a higher porosity than Baffle A, Baffle B is a more desirable baffle to use for compartmentalizing the vessel. Therefore, it was decided to use only Baffle B for the testing with the hemispherical head.

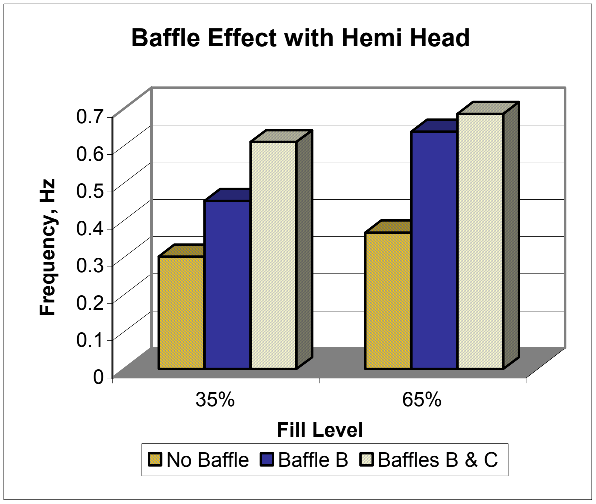

Figure 4

In Figure 4, the natural frequencies of three configurations for a vessel with hemispherical heads is shown. The no-baffle data is shown to have a low natural frequency. Adding Baffle B at 66% of the vessel length (seam-to-seam) shifts the natural frequency of the compartment up by a noticeable amount. Adding Baffle C, a dampening baffle, at 33% of the vessel length also shifts the natural frequency, but the shift is not as much as would be predicted if it were a compartmentalizing baffle rather than a dampening baffle.

Dampening Baffle. Adding a dampening baffle to the system will reduce the wave crests that are created when a vessel is exposed to motion. Figure 5 shows this effect.

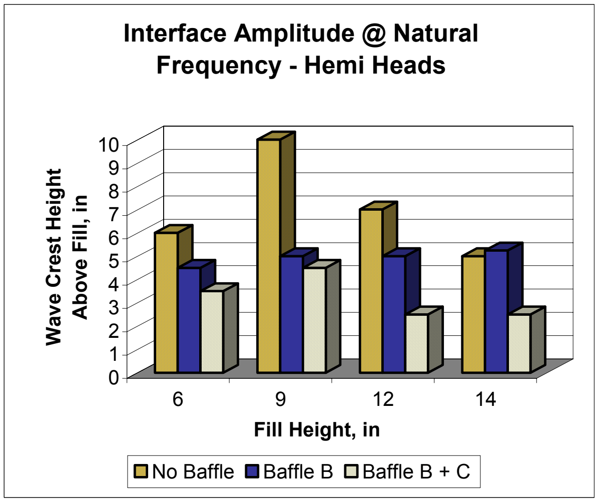

Figure 5

The amplitude of the wave crest is shown for the bare vessel with no baffling, for Baffle B at 66% of the vessel length, and then for Baffle C at 33% of the vessel length in addition to Baffle B at 66%. These amplitudes are given for the natural frequency for each arrangement, a worst-case picture. Even though each data point is in a natural frequency situation where wave crests are at their worst, there is still dampening that occurs with the addition of Baffle C. Comparison at a single frequency, for example the natural frequency of the bare vessel, would show even more interface amplitude dampening.

Even though Baffle C is in the dampening category, it still does have some compartmentalizing effect, with a frequency shift. However, this shift is not as much as would occur with a true compartmentalizing baffle.

Wave Amplitudes Away From Natural Frequency. The best vessel design will maintain the natural frequency of any compartment at twice the driving frequency of the FPSO. If the driving frequency is less than fifty percent of the compartment natural frequency, no further baffling will be required. However, if the driving frequency is between fifty and eighty percent of the compartment natural frequency, additional dampening will be required. If the driving frequency is greater than eighty percent of the compartment natural frequency, the compartment must be further compartmentalized.

Figure 6 illustrates the amount of dampening that occurs as the driving frequency moves away from the natural frequency. In this figure, the no-baffle configuration is compared to the vessel with Baffle B installed at 66% of the vessel length. The wave amplitude for four fill levels is shown, with imposed frequencies at 80%, 100%, and 120% of the natural frequency.

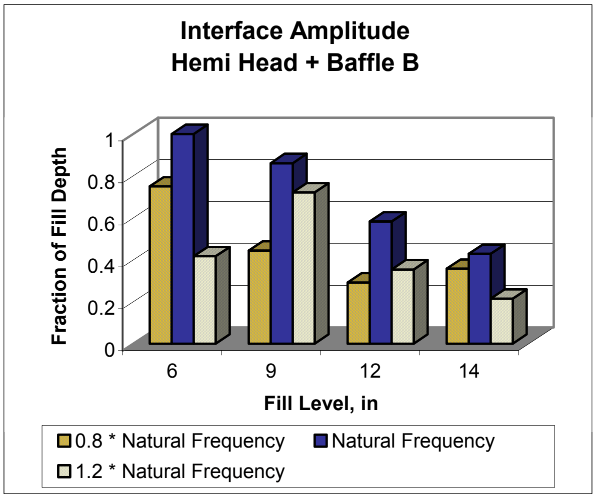

Figure 6

The amplitudes demonstrate a noticeable shift as the driving frequency is moved away from the natural frequency. A glance at the data would seem to indicate that moving either direction from the natural frequency would yield the desirable wave amplitude reduction. It is dangerous to design the vessel for a driving frequency above the natural frequency of a compartment because of the risk of meeting a second or third harmonic.

We suggest designing the separator system so each compartment in the vessel has a natural frequency around one half of the FPSO. This may not always be possible, however, so further consideration must be given to the vessel design. With the imposed frequency at 80% of the natural frequency of the long compartment created by Baffle B, there are still significant wave crest heights. This indicates a need to add a dampening baffle to the system, if further compartmentalization is not an option. This configuration is shown in Figure 7.

In this figure, the bare vessel without baffles is again compared to a configuration with both Baffle B and Baffle C. As in Figure 5, Baffle B is at 66% of the vessel length, and Baffle C is at 33% of the vessel length. A comparison of Figures 6 and 7 shows that the wave amplitudes are reduced when Baffle C is added to the vessel configuration.

The possibility of reaching a harmonic situation is demonstrated by the 9-in. fill data. In this data, the wave amplitude actually increases at a higher frequency. This is due to a harmonic multiple of the slight frequency shift that is created with the addition of a dampening baffle.

Summary of Results. The results obtained by model testing a 24 in. ID x 72 in. long, horizontal cylindrical vessel subjected to pitch clearly demonstrates the need and advantages for conducting model studies. Vessel configurations including head type, baffle selection, and baffle placement produce both shifts in the natural frequency as well as changes in the interface displacement. These tests confirm that baffles of low porosity will behave like solid walls while those with greater porosity produce wave amplitude reductions with little shift in the natural frequency.

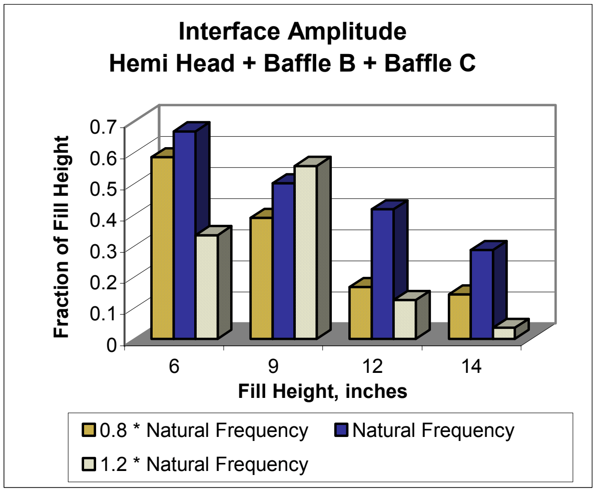

Figure 7

The data suggests that maintaining effective separation requires the FPSO separator design to have compartment natural frequencies at least 20% above the driving frequency. For severe seas dampening baffles can be used to further reduce the interface amplitude.

Bohai Bay Sea States

The primary function of any separator must be to achieve adequate phase separation during a wide range of operating conditions. For example, an FPSO tanker located in Bohai Bay, China could be subjected to the following ocean-induced 1-year storm, 10 year and 100-year storm motions.

1-Year Sea States	
Significant Wave Height	8.95 ft.
Mean Wave Period	6.35 s
Maximum Wave Height	16 ft.
Maximum Wave Period	8.06 s

10-Year Sea States	
Significant Wave Height	13 ft.
Mean Wave Period	7.65 s
Maximum Wave Height	22.8 ft.
Maximum Wave Period	9.72 s

100-Year Sea States	
Significant Wave Height	16.8 ft.
Mean Wave Period	8.58 s
Maximum Wave Height	28.6 ft.
Maximum Wave Period	10.90 s

When subjected to these wave amplitudes and periods, an FPSO facility will move in a cyclic pattern determined by facility and mooring type, vessel weight, center of gravity and center of balance location. The separator designer requires a definition of the six degrees of motion for four operating conditions, including displacement, period and acceleration for each.

Operation Conditions. The four operating conditions are as follows:

Normal operation – This is generally calm seas with small waves. The FPSO facility amplitudes are low and the cycle periods are usually short. The process is expected to perform at its specified rates and effluent quality when subject to these sea states.

1-year storm operation – These storms are generally mild to moderate in nature producing slight increases in wave amplitude and longer wave periods. Depending on severity it is not uncommon for the production equipment to continue operating at the specified rate and effluent quality during these storms.

10-year storm operation – As seen in the sea states tabulated above, a 10-year storm produces greater wave amplitudes at even longer periods. Although these storms are considered moderate to severe, it is not uncommon for the production equipment to continue to operate. However, the effluent quality cannot normally be maintained during these sea states. Continuing to operate during these storms reduces the likelihood that equipment could be damaged during a shutdown.

100-year storm operation – Once again, the wave amplitudes increase and the wave periods are at even longer periods. These storms are extremely severe and equipment survival is the key concern. In all severe storms the production is shutdown and processing equipment is either drained or filled as necessary to ensure survival.

Separator Design for Bohai Bay

For our example, we have chosen to size a three-phase separator for an application in Bohai Bay. The production parameters are:

Gas Flow	5 MMscfd
Gas Gravity	0.85
Oil Flow	30,000 bopd
Oil Gravity	16 API
Water Flow	20,000 bopd
Water Gravity	1.01
Operating Temperature	200 °F
Operating Pressure	150 psig
Oil Retention Time	20 minutes
Water Retention Time	20 minutes

Land-based Separator Design. Based on these process conditions, a typical fixed separator would be sized at 144 in. ID x 55 ft. T/T with an L/D ratio of 4.5. To achieve the required 20 minutes of retention time for the water phase, the oil/water interface is located at 35% of the vessel diameter. The oil/gas interface would be located at 65% of the vessel diameter. As shown in Figure 8, placing a baffle with low porosity near the inlet nozzle will contain the turbulence created by high velocity fluids entering the vessel. The baffle also functions to distribute fluids into the quiescent zone.

To ensure maximum retention time a second low-porosity baffle is recommended to be installed ahead of the fluid exits. Since the separation should have been completed by the time the fluids reach this baffle, re-mixing of the fluids should not be a problem. This baffle has been shown in CFD studies to effectively isolate the outlets from the quiescent zone. Isolating the outlets in this fashion effectively prevents oil and water from channeling toward them. When additional coalescence and separation performance is required, coalescing media is installed to 1) provide additional surface area for separation, 2) reduce the turbulence of the oil and water streams, and 3) provide a conduit for the separated oil, water and gas to their respective interfaces.

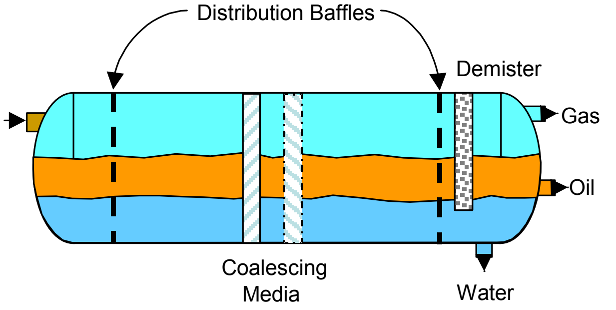

Figure 8 – Land-Based Separator Design

By isolating the quiescent zone with distribution baffles at each end of the vessel, the actual retention time is permitted to approach the theoretical retention time. In CFD studies, these baffles have been shown to nearly double the actual retention times by effectively eliminating all short-circuiting.

FPSO-Based Separator. If this long separator were installed on an FPSO, the oil/gas interface motions would be amplified as much as eight times. To illustrate the severity of this effect, an amplification factor of only four would result in amplitudes of two feet when the FPSO was pitching as little as 1°. With the FPSO pitching 4°, the oil/gas interface would be out of control and splashing against the top of the vessel. High interface amplitudes will increase the gas velocity, resulting in the formation of an oil spray that may flood the mist extractor. After the mist eliminator is flooded, liquids carryover in the exiting gas will develop.

Generally, to reduce this amplification effect it is customary to reduce the L/D ratio to approximately three to achieve better interface control for an FPSO-based separator as shown in Figure 9. Designing with a reduced L/D ratio of three results in an FPSO separator size of 168 in. ID x 40 ft. T/T. The interface levels remain at 35% and 65% for the oil/water and oil/gas, respectively, to achieve the 20-minute retention times for the water and oil.

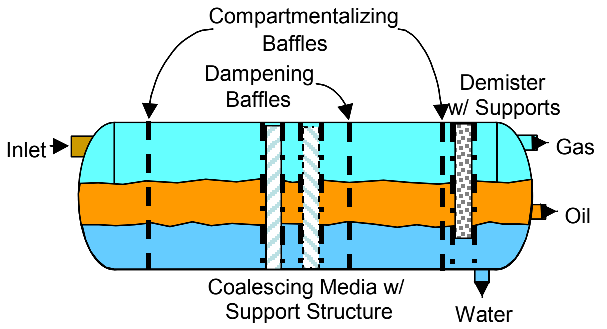

Figure 9 – FPSO-Based Separator Design

Although the vessel is shorter, effective interface control will require additional baffles to increase the frequency of the interfaces to at least twice the ocean frequency. (In other words, the period of the fluids in the separator must be at least ½ the period of the host vessel.) Using a low-porosity baffle as the inlet distribution baffle effectively establishes a compartment between the baffle and head. A low-porosity baffle behaves like a solid plate and effectively confines the wave oscillations to the inlet zone. From the test results we obtained, placing the baffle at four feet from the tangent line yields the following natural frequency and period for the inlet zone:

Interface	Frequency	Period
Oil / Gas	1.3 Hz	0.8 s.
Oil / Water	0.18 Hz	5.5 s.

With facility motion periods at 6.35 seconds in Bohai Bay, the oil / water interface oscillation should not be severe in the inlet and outlet zones. Waldie and White have shown the oil / water interface may have significantly greater amplitudes when driven at the natural frequency than the oil / gas interface.[11] If the interface period is not significantly below the wave period, additional baffling of the oil / water interface may be required.

Placing a distribution baffle ahead of the outlet zone approximately four feet from the tangent will result in the same frequencies and periods as the inlet zone. Again, additional baffling may be required to maintain phase separation and reduce the possibility of re-mixing due to interface motion.

Although not the focus of this study, these additional baffles in the inlet and outlet zones may be horizontal corbels installed just below the oil / water interface. Such baffles used in vertical tanks have been shown to be highly effective at controlling interface oscillations.

When the compartmentalizing distribution baffles are installed to establish the inlet and outlet zones, a 32-foot long quiescent zone is created between these baffles. Using the results of this study the quiescent zone has the following frequency and period.

Interface	Frequency	Period
Oil / Gas	0.37 Hz	2.7 s.
Oil / Water	0.053 Hz	18.9 s.

When subjected to a 1° pitch the fluids will move about three inches to maintain a level interface. However, if the vessel were operated near the natural period, the interface amplification may be as great as four times, or twelve inches. When subjected to 4° of pitch, the amplified waves may crest at four feet above the interface. Therefore, additional dampening will be required to control the wave amplitude.

Optimized FPSO-based Separator. Further improvements to the FPSO separator design must be done to provide for stability of the oil/water interface. The 18.9-second period of the oil/water interface must be further reduced. This can be achieved by compartmentalizing and dampening the vessel with short baffles. The most useful approach is to install nine alternating dampening and compartmentalizing baffles through the thirty two-foot quiescent zone on 3.2 foot spacing. The resulting period for the oil / water interface is

Interface	Frequency	Period
Oil / Water	0.20 Hz	4.9 s.

Not only will this combination of baffles establish a short period they also can reduce the interface amplitude by as much as 50%.

Since these baffles are likely to promote some mixing of the interface additional separation performance can be achieved by placing coalescing media near the end of the quiescent zone in place of a dampening baffle as shown in Figure 10. With these compartmentalizing and dampening baffles in place, this FPSO separator should operate very well in Bohai Bay.

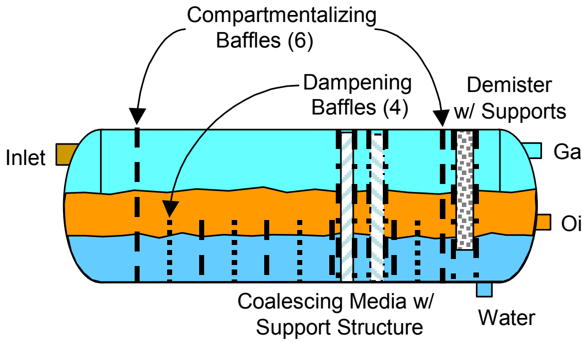

Figure 10 – Optimized FPSO Separator Design

While the design and placement of baffles is critical to maintain the process performance during mild to moderate sea states, it is equally critical that FPSO operating procedures such as filling, draining, shutdown and maintenance be conducted in accordance within proper guidelines. It is also crucial that the impact forces and component fatigue be properly accounted for in all FPSO vessel designs. While not a specific part of this study, the impact forces on baffles were estimated to be in excess of 0.6 psi when the interface was oscillating at the natural frequency. In a 14-ft ID vessel, an impact pressure of 0.6 psi would produce forces in the order of 13,000 pounds. This impact load must be contained by supports and braces to prevent unnecessary damage to the vessel internals.

Conclusions

This paper highlights the need to develop an inclusive separator operating philosophy that included filling, draining, shutdown and maintenance as well as a plan to handle pending and passing storm conditions. To aid in the development of this philosophy a separator model was tested using various configurations. These configurations were subjected to pitch motion on a simulation table utilizing a water-air interface. Interface amplitude data was recorded over a wide range of driving frequencies and fluid levels. The data was used to determine the natural frequency of each vessel configuration. The theoretical natural frequency was then determined for each configuration and a natural frequency parameter was determined to permit extrapolation to full-size FPSO separators.

The data clearly shows a significant variation in natural frequency as the vessel configuration is altered. As expected, frequency was determined to be a function of fill height and baffle placement. However, the data also showed the natural frequency parameter was a function of head type and baffle/head configurations. Tests focusing on the role of baffle porosity confirmed that baffles with low porosity served to compartmentalize the vessel and at higher porosity dampened the interface waves.

Using this collected data, a large FPSO-based separator was designed for an application in Bohai Bay for a 16 API crude oil, where ocean wave periods are uncharacteristically short. As needed, compartmentalizing baffles were used to segment the vessel, distribute the fluids, maximize the residence time and increase the natural frequency. Where high velocity might produce detrimental fluid shear and mixing of the separated phases, higher porosity baffles were used to reduce the interface amplitude without significantly shifting the compartment natural frequency.

The data permitted the development of a separator design that ensured the natural frequency of the interfaces were above the natural frequency of the driving frequency at all fluid levels. The design also reduced the interface amplitude by combining frequency selection with interface dampening. The result was an FPSO separator design that, if operated properly during severe and storm seas, should maintain effective separation performance over a wide range of mild to adverse sea states.

Nomenclature

g = acceleration of gravity, 32.2 ft/s^2
h = fill height, ft.
ℓ = length of vessel or compartment, ft.
γ = dampening factor, dimensionless
λ_n = natural frequency parameter for mode n, dimensionless
ρ_w = density of water at operating conditions, lb/ft^3
ρ_o = density of oil at operating conditions, lb/ft^3
ω_n = experimentally determined natural frequency at mode n, rad/s.

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