Design of a Cyclonic-Jetting and Slurry-Transport System for Separators

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Summary

Sand and solids are removed from production separators either off line (shut down for physical removal) or on line by use of jetting systems. Traditional jetting designs use spray nozzles to fluidize and push the sand toward a covered outlet to evacuate the solids from the vessel. Cyclonic-jetting technology combines the fluidization and evacuation functions into a single, compact device. On the basis of a hydrocyclonic platform, this technology converts jetting spray water into shielded vortex flow that fluidizes sand in a circular zone without disturbing the oil/water interface.

Total solids removal is primarily a function of set height, spray flow, and spacing. A single unit was optimized at a set height of 10 cm (4 in.) with spray pressure of 0.7 barg (11 psig) to provide an area of influence of 1.1 m² (12.0 ft²) with 28 cm (11 in.) of sandbed depth. Placing two units in parallel with overlap of their affected zones reduces the "egg-carton" effect associated with this technology; however, optimum operation, in terms of total sand removed, occurs when the units do not overlap. Slurry at up to 60 wt% solids is transported from the jetting system to the handling equipment. The boundary design conditions for slurry transport are erosion velocity (upper limit) and particle-transport velocity (lower limit). By use of published models, the piping design for a four-unit cluster of cyclonic-jetting devices was validated at 5.0-cm (2-in.) nominal size. Integration and operation of a jetting system with transport, dewatering, and disposal stages of facilities sand management are presented as guidelines for system design.

Produced Solids in Separators

Oil and gas wells often produce sand or solids with the well fluids. Even with exclusionary well design, solids will report to the surface facilities through equipment failure, completion limitations, or a step change in production profile, such as water breakthrough. In addition, an operating model of sand coproduction is becoming more relevant as a method of improved oil recovery (Geilikman et al. 1994; Ahmad et al. 2004; Andrews et al. 2005). Facilities sand management is tasked with ensuring sustained hydrocarbon production when particulate solids are present in well fluids, while minimizing the impact of these produced solids on surface equipment (Rawlins 2013).

Produced solids may erode chokes and flowlines, but the first place of accumulation in large quantities is the production separator (Tronvoll et al. 2001; Chin 2007; McKay et al. 2008). Solids settle in production vessels and piping when the transport velocity drops below the limiting deposition velocity. The preferred location for facilities sand removal is before the choke with a wellhead desander (Rawlins 2013); however, in cases where this technology is not currently used, the produced solids will collect in the primary separating vessel. Accumulated solids in gravity-settling vessels result in loss of residence time, corrosion-enhancement zones, increased sediment in oil, increased oil content in produced water, and degraded injectivity of produced water (Andrews et al. 2005). Sand and solids are removed from production separators either off line (shut down for physical removal) or on line by use of a jetting system.

Static, settled solids within a production separator become harder to remove as time increases because of consolidation and binding. Consolidation is a mechanical effect whereby the sand rearranges to a more-compact state by removal of liquid between the grains. Gravity, time, fluid lubrication, and vibrations from platform and equipment all work together to consolidate the sand. Binding occurs when foreign materials bridge between or cement together the sand grains. Wax, asphaltene, precipitates, bitumen, corrosion products, bacteria, scale, iron sulfide, and production chemicals can all lead to binding. The decrease in pressure and temperature in the production separator, compared with tubular and wellhead conditions, may accelerate the binding effect. Consolidated or bound sand requires chemical, thermal, or mechanical action to return to a free-flowing state. An efficient jetting-sand-removal system must therefore move or remove the solids while they are still capable of being fluidized.

Traditional Sand Jetting

Several approaches exist for removal of accumulated sand from production separators. The most basic requires isolation of the vessel and manual removal of the sand (McKay et al. 2008; Rawlins 2013). This method has low capital expenditure but results in loss of production. Alternatively, various separator internal devices can provide online sand removal, which negate the need for equipment isolation and vessel entrance. These devices include spray jets and pans (Chin 2007), conveyance sprays (Fantoft et al. 2004), vortex desanders (Jasmani et al. 2006), and eductors (Coffee 2008). These devices typically fall under the general moniker of "sand jetting," even though they may not use specific jet-spray devices. Each of these devices should be designed to remove sand accumulated from the water zone with minimal interference at the oil/water interface.

The most-common approach for on line separator sand removal is the traditional jet and pan system. A schematic of this type of system is shown in **Fig. 1.** Spray water is introduced through an internal piping header aligned axially along the separating vessel. Spray nozzles are spaced along the header to introduce a jet of water that fluidizes and pushes the sand toward the bottom middle of the vessel. A sand pan (inverted V-trough with triangular slots) or sand cap (flat circular plate) direct the sand toward the outlet nozzle and prevent vortex formation.

While this equipment is widely used by operators, engineering companies, and equipment fabricators, no sizing guidelines are given in the most commonly referenced production-separator-design procedures, such as *API Publication 421* (1990), *NORSOK Standard P-100* (2001), DEP 31.22.05.12-Gen (Shell GSI 2008), Gas Processors Suppliers Association (GPSA) Engineering Data Book (GPSA 2004), and the work of Arnold and Stewart (1986). Many anecdotal papers have been published showing general jet and pan layout, but only Priestman et al. (1996) have published a detailed analysis for this type of system. The reader is referred to their excellent paper for full technical details on jet design and spacing, fluidization factor, drain spacing, and solids-evacuation procedure. Of key note from their recommendations is partitioning of the vessel into discrete wash loop zones, with each zone having a length at three times the vessel diameter. The jet and pan internals are designed for a single zone and repeated along the length of the vessel.

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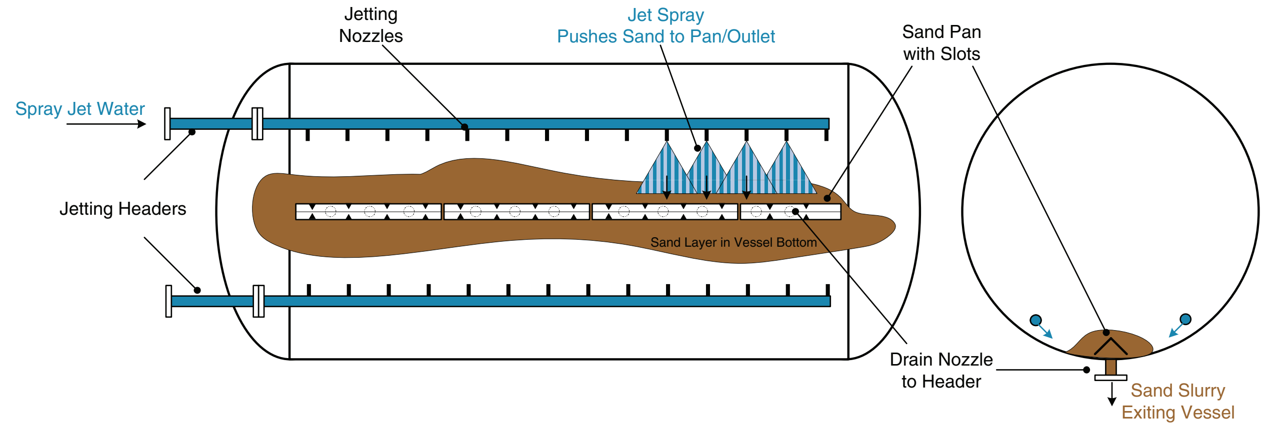

Fig. 1—Schematic of jet and pan system for solids removal from production-separating vessels.

Cyclonic-Jetting Technology

The cyclonic-jetting device is an alternative technology to the jet and pan design, and was developed to provide more-efficient solids removal with less interference at the oil/water interface. Cyclonic-jetting technology uses the flow pattern from a standard solid/liquid hydrocyclone to combine fluidization, evacuation, and hydrodynamic transport of particulate solids. Cyclonic technology is extremely versatile and can be used to clarify liquid or gas, concentrate slurries, classify solids, separate immiscible liquids, degas liquids, demist gases, wash solids, break agglomerates, and mix phases (Svarovsky 1984). The principle and basic design of the solid/liquid hydrocyclone was first patented in Bretney (1891) (US 453,105). As a unit process, cyclones have the highest throughput/size ratio of any classification device.

Operating Principle. A hydrocyclone is a static device (unlike a centrifuge) that generates centrifugal force through fluid pressure to create rotational fluid motion (Green and Perry 2008, Chapter 15). **Fig. 2** (left) shows a schematic of a hydrocyclone of conven-

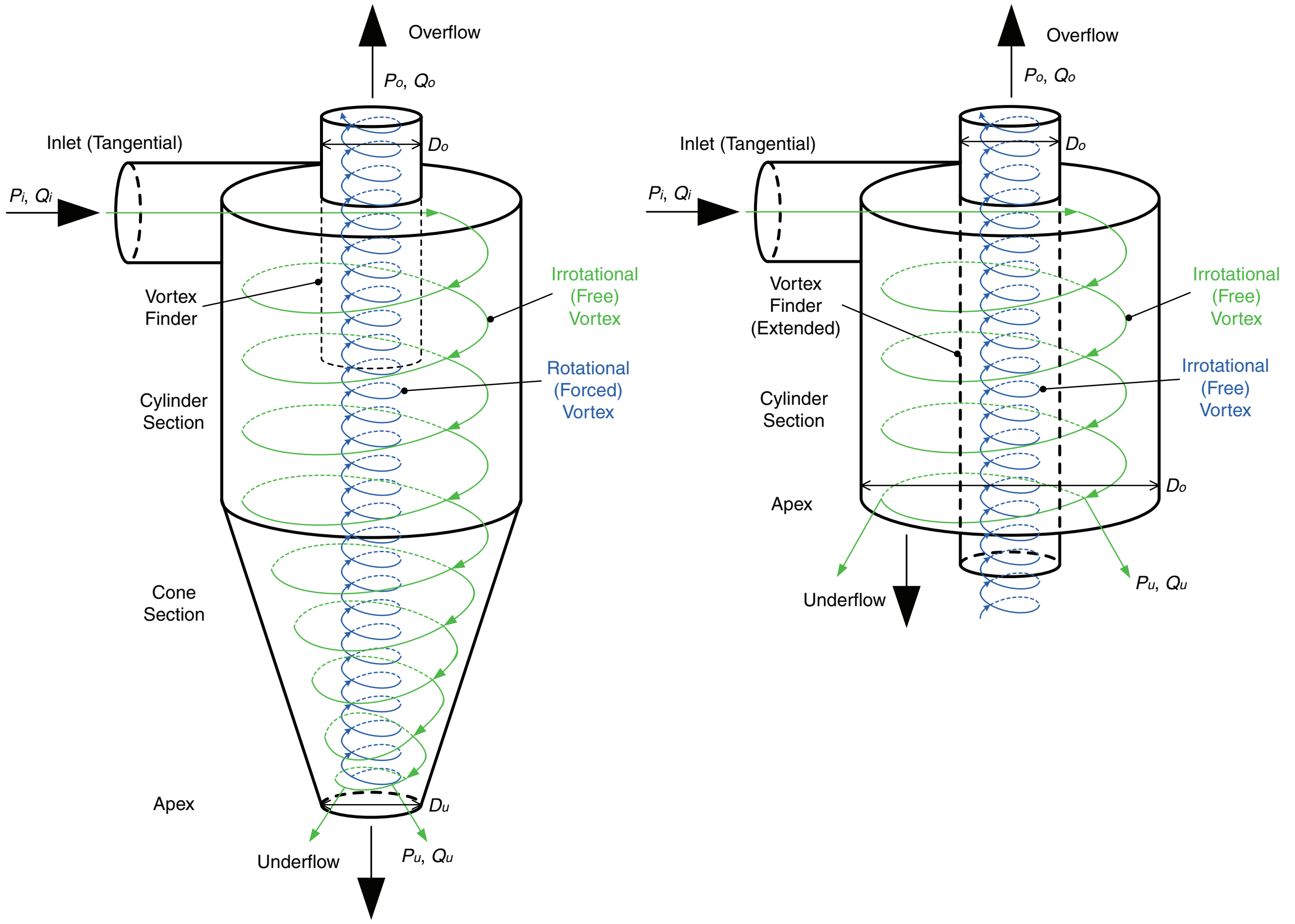

Fig. 2—Schematic of standard-hydrocyclone (left) and cyclonic-jetting-device (right) geometry and flow patterns. The standard hydrocyclone operates with $P_i > P_u = P_o$, $PDR = 1.0$, and $S \approx 0.20$. A cyclonic-jetting device operates with $P_i > P_u > P_o$ and $PDR = 1.3$ to 1.5 (S is infinite, based on standard definition; however, external controls result in a system with $S = 1.0$).

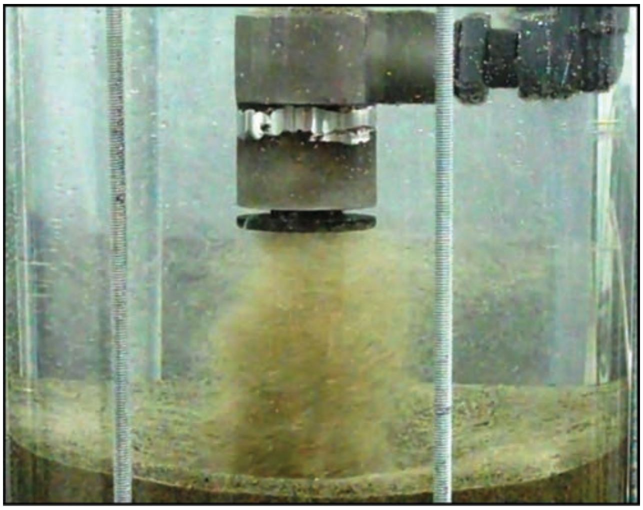

Fig. 3—Shielded vortex sand removal demonstrated by cyclonic-jetting device within a transparent pressure vessel.

tional design, along with the helical flow patterns produced. Fluids are introduced tangentially into a stationary cono-cylindrical body to produce the characteristic vortex flow. A pressure differential ($P_i - P_o$) drives the fluid throughput, and the tangential inlet to a cylindrical section changes the incoming pipe axial flow to rotating flow. A vortex finder extends into the cylindrical section to form an annulus wherein an irrotational (free) vortex is formed. This vortex travels down the cylinder and into the cone section wherein the reduction in diameter increases the angular velocity of the fluids. A second rotational (forced) vortex exists at the center of the hydrocyclone and is located by the vortex finder. The free and forced vortices are coupled throughout the open length of the hydrocyclone.

Fluids discharge freely from both the overflow and the underflow orifices. The flow split (S), shown in Eq. 1, is the underflow volumetric flow rate (Q_u) divided by overflow volumetric flow rate (Q_o), and is governed by the two discharge orifice diameters (D_u and D_o) and the pressure-differential ratio (PDR). The *PDR*, shown in Eq. 2, is the inlet/overflow pressure drop divided by the inlet/underflow pressure drop. In terms of geometric parameters, empirical correlations for S have the form $S = (D_u/D_o)^x$, where x ranges from 3.0 to 4.4 (Plitt 1976).

$$S = {Q_u}/{Q_o} = \left({D_u}/{D_o}\right)^x \quad \text{...(1)}$$

$$PDR = \frac{P_i - P_o}{P_i - P_u} \quad \text{...(2)}$$

The standard hydrocyclone operates at $P_i > P_u = P_o$. The overflow and underflow pressures are atmospheric; therefore, $PDR = 1.0$. At this *PDR*, and using hydrocyclone geometry with $D_u = 0.5D_o$, the solids-free flow split averages 0.20. At atmospheric discharge, 80% of the feed liquid reports to the overflow stream. A siphon can be induced onto the overflow piping to reduce the flow split to 0.10 to 0.15, thus pulling more liquids to the overflow (i.e., $P_i > P_u > P_o$ and $PDR = 1.1$ to 1.2). The increase of liquid flow to the overflow stream imparts a higher suction force at the apex, which coarsens the separation size (Alexander 1975).

The right schematic in Fig. 2 shows the flow pattern of a cyclonic-jetting unit. The geometric differences compared with the hydrocyclone are truncation of the cone and extension of the vortex finder. Because of the extension of the vortex finder, the two hydrocyclone vortices are uncoupled. The outer irrotational vortex still exists and discharges from the apex. The discharging swirling flow imparts rotational motion below the device, which induces an internal irrotational (free) vortex. The internal vortex is located by the vortex finder. Because all the inlet fluid reports to the outer bottom discharged vortex, on the basis of the traditional definition, S is infinite ($Q_i = Q_u$ and $Q_o = 0$, $\therefore$ $S = 1/0$). However, a system *PDR* of 1.3 to 1.5 is imposed to draw fluid up through the vortex finder, thus balancing Q_u and Q_o. Therefore, effective $S = 1.0$. Differential pressure between the operating vessel containing the cyclonic-jetting unit and the slurry-discharge point ($P_u > P_o$) creates a suction for solids evacuation. This differential pressure can be provided by elevated operating pressure within the vessel or the external eductor located on the slurry-outlet piping.

The external vortex discharging from the cyclone body forms a discrete spray angle > 90° that fluidizes the sand below and around the device. Within this spray cone, the internal vortex picks up the sand in a swirling motion to report through the vortex finder and discharge with the overflow stream. A photograph of this action with a single unit inside a transparent pressure vessel is shown in **Fig. 3.** The action of the external vortex to induce the internal vortex, fluidize the sand, and form a discrete volume within which the sand is removed is termed "shielded vortex sand removal."

Installation in Production Separators. Most production separators have a horizontal orientation to accomplish sufficient residence time and surface area for gas/oil/water dissociation. Sand that has settled into the water zone of these horizontal separators is removed with multiple cyclonic-jetting devices, as shown in **Fig. 4.** The cyclonic-jetting units are connected to two internal headers. The first delivers spray water to each unit, while the second header transports the evacuated slurry. The cyclonic-jetting units are placed at a set height above the vessel bottom and spaced to provide coverage of the sand layer. The influenced area (affected zone) of each unit has an ellipse shape, and the center-to-center spacing is aligned to provide minimal overlap between corresponding major axes of each ellipse.

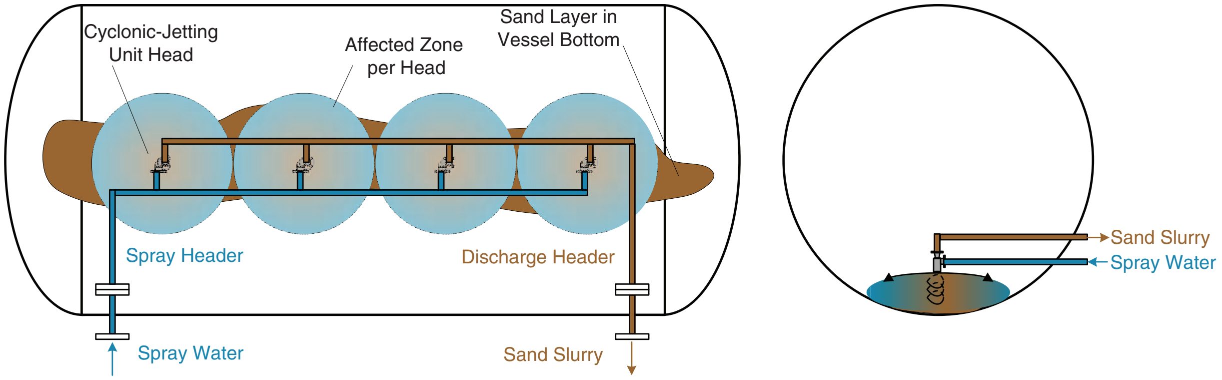

Fig. 4—Schematic of cyclonic-jetting system for solids removal from production-separator vessels.

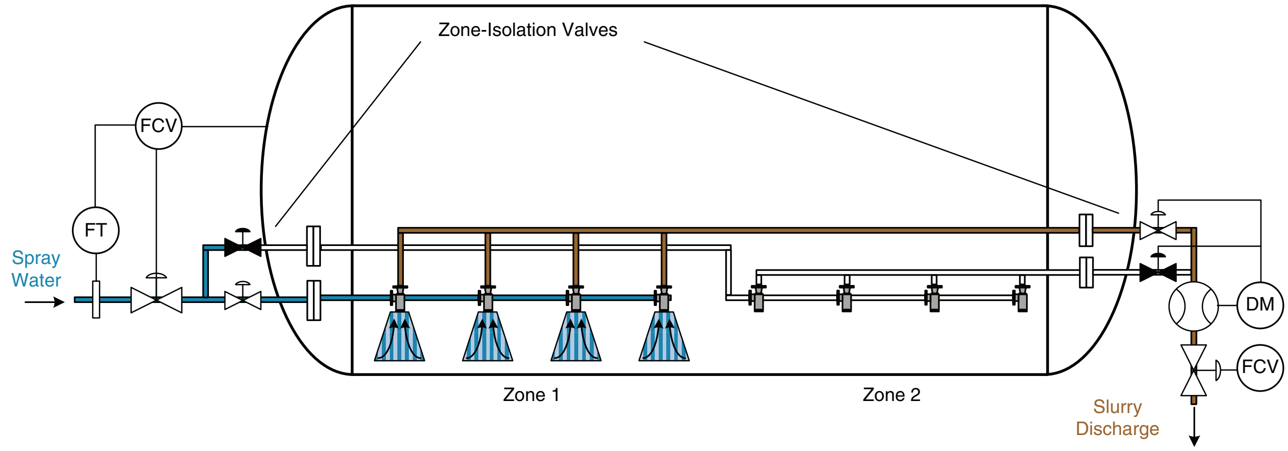

Fig. 5—Process-flow schematic for zone operation of cyclonic-jetting cluster. (FT = flow transmitter.)

Small-diameter (≤ 2.0-m) horizontal vessels require a single row of units located axially along the centerline of the vessel, while large-diameter (> 2.0-m) vessels require two rows placed to straddle the vessel centerline. In a dual-row system, each cyclonic-jetting unit is oriented at 15° away from the vertical centerline. Vertical vessels with a small diameter (< 1.5 m) require a single device placed at the centerline, while large-diameter (> 1.5-m) vessels require multiple units at appropriate spacing or a cone bottom (false or pressure-retaining) to bring the sand to a smaller collection area.

Each cyclonic-jetting device requires pipe connections for spray and evacuation functions. The inlet and outlet piping for a single unit has a nominal diameter of 2.5 cm (1 in.). Multiple units are aggregated into a cluster, with a maximum of four units per group. The inlet/outlet piping for a cluster is a nominal diameter of 5.0 cm (2 in.). Each cluster treats a separate zone within the vessel, with each zone operated independently, and only one zone treated at a time. Each zone, therefore, requires a pair of connections—one for the spray header and one for the slurry-evacuation header, as shown in **Fig. 5.** Zone-isolation valves activate each zone in sequence.

The inlet (spray) piping header requires either a pressure-control valve (PCV) to provide water at the design pressure above the vessel operating pressure, or a flow-control valve (FCV) linked to provide the required spray flow for the corresponding number of cyclonic-jetting devices. Fig. 5 shows the configuration using flow control. The outlet (slurry) piping header requires a similar setup with either a PCV or FCV used to regulate the flow of slurry discharging from the production vessel. The slurry outflow and spray inflow are controlled to the same values to maintain level integrity within the separator. The slurry line-control valve can be installed after a desanding hydrocyclone to minimize wear of the valve components, or a suitable slurry valve/choke can be set directly on the slurry discharge line. Each zone is operated until sufficient solids are removed. The recommended method is to monitor the slurry-discharge concentration with a gamma ray densitometer (shown as DM on Fig. 5). Once the concentration drops below 5 wt% solids, the slurry discharge and spray flow for that zone are stopped, and the next zone is activated.

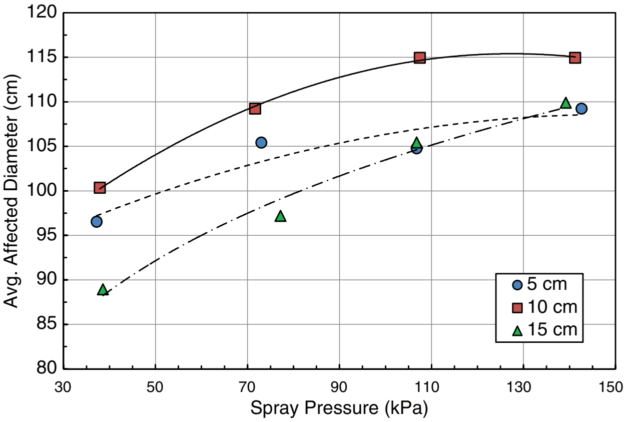

Fig. 6—Effect of spray pressure on average affected diameter for a single cyclonic-jetting-device unit at three set heights. Test conditions include vertical orientation in an atmospheric horizontal vessel (2.5-m internal diameter), 28-cm total sand depth, sand with density of 2640 kg/m^3 and average particle size of 420 µm, and eductor-generated discharge flow.

Variables Affecting Sand Removal. Cyclonic-jetting-device solids-removal performance is measured by affected area within the sand layer. The affected area, measured as the top area of the influenced (fluidized and evacuated) ellipse, is a function of the set height, spray pressure, sand depth, installation angle, and particulate properties, such as density and particle-size distribution. The effects of set height, spray pressure, sand depth, and unit head angle are detailed at present. The effects of particulate and fluid properties are still being investigated and are only briefly discussed. All data presented were generated from laboratory testing using sand with density of 2640 kg/m^3 in fresh water (1005-kg/m^3 density and 1.0-cp viscosity). The test sand had a top size of 2360 µm and a median size of 420 µm. This material had very little fines, with only 0.05 wt% at less than 53 µm.

The effect of set height and spray pressure is shown in **Fig. 6.** Set height is the vertical distance between the vessel shell and the bottom edge (evacuation inlet) of the device, while the spray pressure is the header pressure of the spray water delivered to a unit. Fig. 6 shows the effect of these variables on average affected diameter. The influenced area from a single cyclonic-jetting device has an ellipse shape, so the average affected-area diameter is the mean value of the major and minor axes of the influenced ellipse. The data in Fig. 6 are shown for a single unit at vertical orientation with 28-cm (11-in.) sand depth. Discharge flow was generated through an eductor from an atmospheric horizontal vessel and was held constant for all tests. At these conditions, the 10-cm (4-in.) set height produced a higher average affected diameter compared with 5-cm (2-in.) and 15-cm (6-in.) settings. The peak diameter value was 115 cm (45 in.), which can be achieved at a fluidizing flow pressure of 110 kPa (15 psi). Increasing spray pressure, at a set height of 10 cm (4 in.), did not increase the affected area.

Fig. 7 shows the effect of accumulated sand depth on average affected diameter. Tests were conducted using a single unit at vertical orientation, a 10-cm (4-in.) set height, and 110-kPa (15-psi) spray pressure. Sand depth in the test vessel varied from 2.5 cm (1 in.) to 58 cm (23 in.), and the results show that the affected area increases

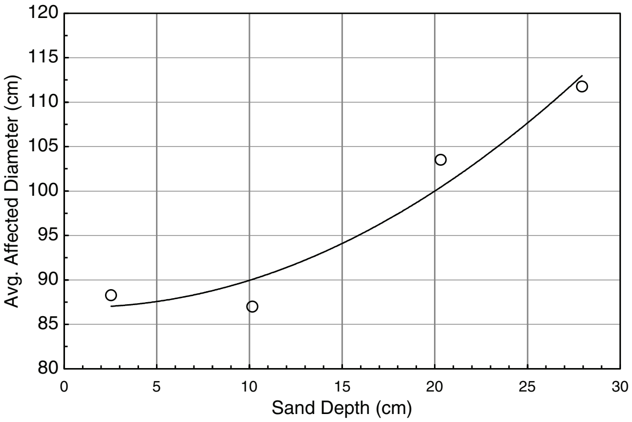

Fig. 7—Effect of accumulated sand depth on average affected diameter for a single cyclonic-jetting-device unit at set height of 10 cm and fluidizing pressure of 110 kPa. Test conditions include vertical orientation in an atmospheric horizontal vessel (2.5-m internal diameter), sand with density of 2640-kg/m³ and average particle size of 420 µm, and eductor-generated discharge flow.

with sand depth. An average affected diameter of 1.0 m (39 in.) is achieved at a sand depth of 20 cm (8 in.), while 2.0 m (78 in.) can be influenced in 58 cm (23 in.) of accumulated sand. The shape of the affected volume forms an inverted, truncated cone. The bottom of this cone is a sand-free area with a diameter of approximately one-half the top average affected diameter. As long as the sand is free-flowing (not consolidated or bound, as previously discussed), the shape of the affected volume will be governed by the particulate material angle of repose. Dry sand has an angle of repose from 30 to 35°, while wet sand has an increased angle at 45 to 60° because of interparticle cohesion from the water. The test sand in the current results exhibited an angle of repose of 45 to 55°. Increasing the angle of repose of the sand should result in a slightly higher amount of sand removed per unit.

Unit head angle, defined as deviation angle from vertical, was tested at both the vessel-centerline and offset-from-centerline positions. With a cyclonic-jetting head located directly above the vessel centerline (directly above longitudinal axis), an orientation of 0° offset (vertical) resulted in the highest affected area. This setup is used for small-diameter (< 2.0-m) horizontal cylindrical vessels. For larger horizontal cylindrical vessels (> 2.0-m), a dual-row system is used to provide coverage for the wider sand layer. The dual-row system straddles the longitudinal centerline of the vessel with equal spacing of the rows, as shown in **Fig. 8.**

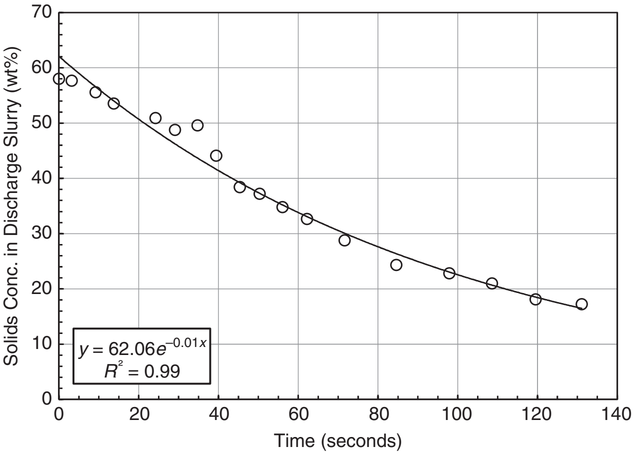

Fig. 9—Concentration of solids in slurry discharging from cyclonic-jetting device. The operating basis is a single unit at vertical orientation in a horizontal vessel operating in fresh water with sand with density of 2640 kg/m³ and average particle size of 420 µm.

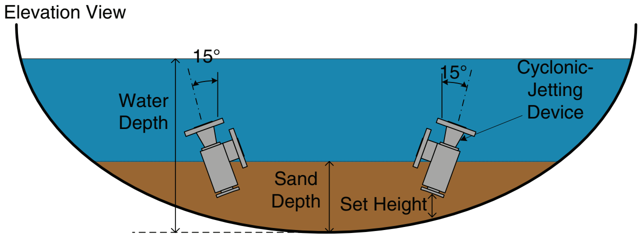

Fig. 8—Location and orientation of cyclonic-jetting heads with dual-row system for large-diameter (> 2.0 m) horizontal cylindrical vessels.

Operation of the cyclonic-jetting heads placed at this position is affected by the curvature of the vessel. Tests were conducted at vertical, positive, and negative deviation angles. The largest amount of sand was removed with a deviation angle of +15°, with the evacuation orifice pointed toward the centerline of the vessel. As sand removal proceeds, sand falls down the vessel shell by gravity toward the centerline. The unit suction is oriented toward the area where the sand is falling, thus maintaining sand removal for a longer time period.

The recommended design parameters for placing cyclonic-jetting units of this design on the basis of the parameters discussed include a set height of 10 cm (4 in.), spray pressure of 75 kPa (11 psi), and center/center head spacing of 120 cm (47 in.). These values are based on balancing spray-water consumption with effective sand removal. These settings resulted in a per-head affected area of 1.1 m² (12.0 ft²), which exhibited an ellipse profile with a major-axis diameter of 120 cm (47 in.).

Slurry-Discharge Concentration. The discharged slurry-concentration profile is shown in **Fig. 9.** These results are from a test at the recommended design parameters. Slurry concentration was measured by rapid-grab sampling during discharge. The initial slurry concentration was 58 wt% solids and showed a decay profile that fits an exponential curve (reaching essentially clear water with 1 wt% solids at 7 minutes). The decay profile is similar to the results by Priestman et al. (1996) in their standard jet and pan tests. They recommended stopping the zone washout when the outflow concentration limit of 5 wt% is reached, which was achieved at 4.2 minutes with the cyclonic-jetting heads. This curve can provide an initial guideline for determination of the zone jetting/discharge time; however, a gamma ray densitometer is recommended on the slurry-discharge line for more-accurate operation.

The slurry-discharge-flow rate is primarily a function of differential pressure between the operating vessel and the delivery point.

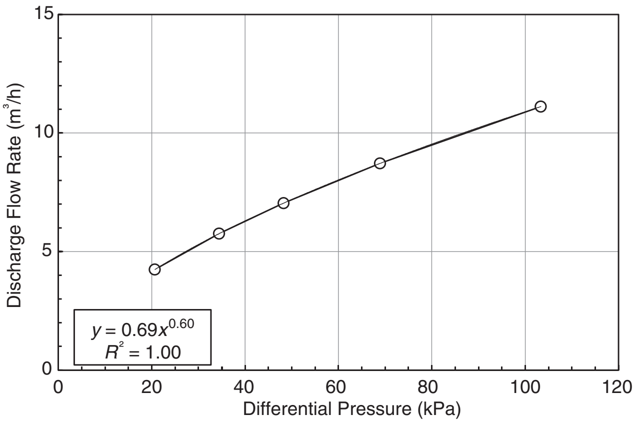

Fig. 10—Discharge-flow rate as a function of differential pressure between vessel operation and delivery point.

Fig. 10 shows the discharge-flow rate as a function of this differential pressure for a single cyclonic-jetting unit. Most systems are sized to operate at 50-kPa (7-psi) differential, which provides a slurry-discharge rate of 7.5 m³/h (33 gal/min) per unit head. The spray flow is then sized to match the discharge flow to prevent changes in operating liquid level of the production separator. This discharge differential pressure must be controlled to prevent drawdown or buildup of the liquid level in the vessel. The maximum cluster size is four operating units, which will have a slurry-discharge-flow rate of 30 m³/h (132 gal/min). This is the volume rate of slurry to be treated by the downstream dewatering and disposal system.

Slurry Transportation

Sand collected by the cyclonic-jetting device is mixed with process water to form a slurry. This slurry is discharged from the production vessel in a controlled manner through delivery piping to a disposal location. The transportation piping must be designed to transport the slurry effectively without allowing the particles to settle and block the piping, while minimizing erosive wear. Erosion rate determines the upper limit of the slurry velocity, while the settling of particles (termed saltation) defines the lower limit. Each zone within the separator will be jetted/washed discretely, and a maximum cluster of four cyclonic-jetting heads are used per zone. The slurry-discharge header piping will be sized for the combined flow from four units, which is 30 m³/h (132 gal/min), and the following analysis is undertaken on this design basis.

Erosion Velocity. *API RP 14E* (1991) is often used to calculate the velocity below which a tolerable amount of erosion occurs. While this method is simple to apply, as shown in Eq. 3, it has been noted to have several limitations. In Eq. 3, V_e is fluid erosional velocity (ft/sec), c is an empirical constant that varies from 100 to 250, and ρ_m is the gas/liquid-mixture density (lbm/ft³):

$$V_e = \frac{c}{\sqrt{\rho_m}} \quad \text{...(3)}$$

A detailed analysis of this method and presentation of a more-comprehensive method are offered by McLaury and Shirazi (1999). The slurry discharging from the cyclonic-jetting device is considered single-phase flow even though it contains sand suspended in water. Using the values of $c = 100$ and gas/liquid-mixture density (ρ_m) of 1057 kg/m³ (66.8 lbm/ft³) for water with 10 wt% salinity yields a maximum velocity of 3.7 m/s (12.2 ft/sec). The McLaury-Shirazi model for single-phase flow predicts a much larger value at > 30 m/s (> 100 ft/sec), as estimated from their Figs. 6 through 8 (McLaury and Shirazi 1999) and using zero superficial gas velocity. Use of the more-conservative velocity, along with the design-discharge-flow rate, shows that flow from a four-unit cluster requires a pipe with a nominal diameter of 5 cm (2 in.).

Horizontal and Vertical Transport Velocity. Slurry transportation in piping is a complex subject, and several treatises are available for an in-depth analysis of the subject (Govier and Aziz 1977; Wilson et al. 2006). *Perry's Chemical Engineers' Handbook* (Green and Perry 2008, Chapter 6) provides a summary of this work and recommendations for calculating the minimum transport velocity for settling slurries. In horizontal piping, the minimum transport velocity (V_{MT}) is given by the Durand equation. Eq. 4 shows this relationship in modified form with the Wasp correction (Poirier 2000) as the last term in parentheses.

$$V_{MT} = F_L\left[2gD\left(s-1\right)\right]^{0.5}\left(d_p/D\right)^{1/6} \quad \text{.................................(4)}$$

In Eq. 4, F_L is an empirical constant influenced by particle size and concentration (Green and Perry 2008, Figs. 6 through 33), g is gravitational acceleration (m/s²), D is pipe diameter (m), s is ratio of solid to liquid density (ρ_s/ρ_l in kg/m³), and d_p is average particle size (m). Use of 1.5 for F_L, 420-µm (10^{-6}-m) silica sand (ρ_s = 2650 kg/m³) in 10 wt% salinity water (1057 kg/m³), and a 2-in. Schedule-40 pipe (D = 0.053 m) yields a minimum horizontal transport velocity of 0.84 m/s (2.8 ft/sec).

For vertical upflow in pipes, the minimum transport velocity is taken as twice the settling velocity (Green and Perry 2008), which can be calculated from Stokes' law. Stokes' law for settling of small particles in viscous fluids is shown in Eq. 5, where V_∞ is the terminal settling velocity (m/s), ρ_s is the density of the solid (kg/m³), ρ_l is the density of the fluid (kg/m³), g = 9.81 m/s², and μ is the fluid viscosity (kg/m·s):

$$V_\infty = \frac{d_p^2 g\left(\rho_s - \rho_l\right)}{18\mu} \quad \text{...(5)}$$

Using the previous data (with $V_\infty = V_{MT}$ and μ = 0.01 kg/m·s) and solving Eq. 5 for d_p yield a maximum lifted particle size of approximately 3 mm. The maximum lifted particle size is one-half this value, so the 2-in. Schedule-40 pipe can carry particles of approximately 6 mm in diameter, which exceeds the horizontal-transport particle size.

From these calculations, pipe-velocity boundary conditions are 0.84 to 3.7 m/s (2.8 to 12.2 ft/sec), with preference toward the higher velocity. Because this slurry-discharge piping does not see continuous use, the upper-limit velocity is very conservative. The jetting system would be used 1 to 2 hr/D only, thus total erosion will be reduced significantly. Two-inch nominal carbon-steel or duplex stainless-steel piping is sufficient for slurry-transport duty; however, the wall thickness must be appropriate for the full system-pressure-design rating.

Piping Design and Operation. *ASME B31.11* (2002) provides slurry-transportation piping-system-design codes that should be followed for basic construction procedures. All piping components should be designed to prevent blockage or settling of solids. Horizontal runs should have sloped construction (1:100 downward orientation). Elbows should be long radius style at minimum, with 5R/10R providing better transition. Elbows should not be placed closer than 10 pipe diameters. Upward runs of pipe are acceptable as long as minimum vertical transport velocity is maintained. Pipe transitions should be eccentric reducers with the flat section at the pipe bottom. Valves should be full-port, with gate or rotating-disk style preferred for long life. Sample ports should be on the side of vertical-piping runs only because horizontal ports may fill up with large particles or plug.

Concentrated slurry should never be introduced into empty piping or process equipment. All piping and process equipment should be prefilled with liquid. This dilutes the introduced slurry and minimizes slugs and associated plugging. The preference is to introduce the concentrated slurry into moving water. In this manner, the slurry-discharge header should be prefilled to the desired operating velocity with solids-free water. The introduced slurry will be diluted and carried away immediately without having a chance to settle. This prefill water can be shut off once the discharge slurry is at the desired flow rate; however, once the cyclonic-jetting device has completed its full cycle, the header piping should be post-flushed with solids-free water to ensure all particles are swept from the system. Proper operation with prefill and post-flush will ensure that no plugging occurs by the discharged slurry.

System Integration

Solids-handling methodology incorporates five steps for full facilities sand-management design: separate, collect, clean, dewater, and disposal (Rawlins et al. 2000). The sand-jetting (jet and pan or cyclonic-type) and slurry-piping components comprise the first two steps; however, the collected slurry must be brought through to

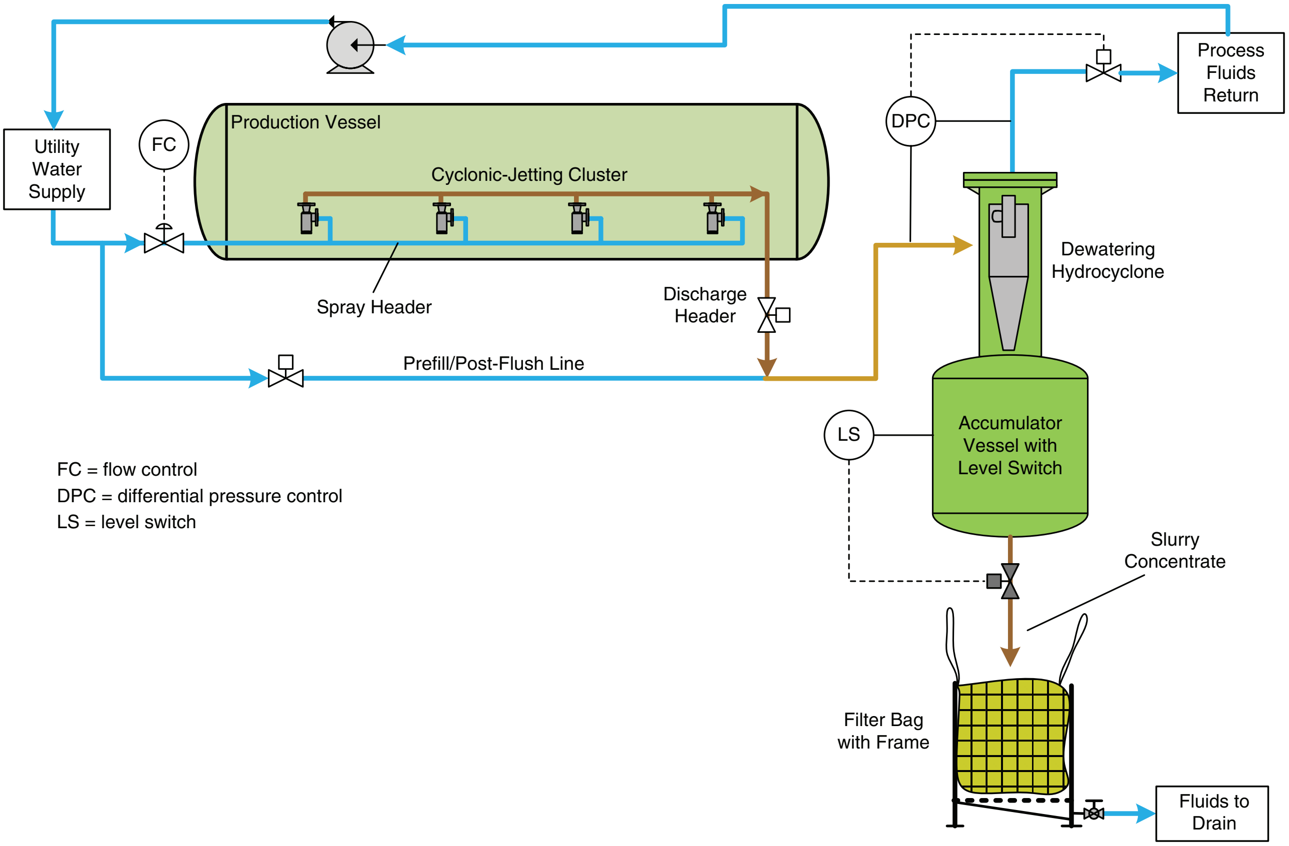

Fig. 11—Process schematic of cyclonic-jetting, slurry-transport, and dewatering system for use in removal of solids from a production separator.

the final disposal location to complete the process. Sand cleaning is only applicable to specific offshore facilities that allow overboard discharge of produced solids and is not detailed in the current discussion. Sand disposal is always required in a facilities sand-management system because the removed sand must be put into some final location; therefore, system integration of jetting and transport with solids disposal is necessary. The author has worked with operators to troubleshoot offshore systems only to find out that jetting equipment was installed into a separator, with subsequent discovery that there was no location to which to transport the slurry or that the sand could not be discharged overboard. These jetting systems were deemed to "not work." However, this designation had nothing to do with the separator internals, but with poor facilities sand-management design leading to process impedance. The target location for slurry disposal must be identified first, and then the jetting and transport system can be designed to match that requirement.

The delivery point for the slurry depends on the required disposal site for the solids. Onshore plants may deliver the slurry to a holding pond, landfill, or injection station. Offshore facilities may add the jetted sand to an existing drill-cuttings disposal bin or caisson. These options simplify solids disposal by use of existing processes. In most cases, an existing solids-disposal route does not exist, and a dedicated scheme must be put in place. **Fig. 11** shows the flow schematic for integrated cyclonic jetting, slurry transport, dewatering, and transport for onshore or offshore locations. Several variations of this flow scheme are applicable depending on the production-vessel operating pressure, level of automation, site-footprint availability, and method of solids disposal. The scheme presented is applicable for a production vessel operating at ≥ 345 kPa (≥ 50 psi).

The flow scheme in Fig. 11 shows a horizontal production vessel with a four-place cluster of cyclonic-jetting devices. Each cluster defines a zone, with larger vessels requiring multiple clusters; however, only one zone (cluster) is operated at a time. This batch methodology allows simple scaleup because the slurry processing equipment stays the same size regardless of the number of zones in the separator. Slurry-handling equipment includes transport piping, a hydrocyclone desander for slurry dewatering, an accumulator sized for multiple batch/cluster collection, and a filter bag/bin for final dewatering and transport.

The first step before operating the cyclonic-jetting cluster is to prefill the discharge header, hydrocyclone desander, and accumulator with clean fluid. These components are brought to a nominal operating velocity in the header and pressure drop across the desander. The discharge header for the cyclonic-jetting devices is then opened to provide slurry to the desander inlet line, with subsequent opening of the spray header to provide fluidizing water on the basis of flow control to the cyclonic-jetting devices. The cluster is allowed to run for the desired time (or outlet solids concentration), and then the spray header and discharge header are closed. The post-flush line is allowed to run until all solids are swept through the desander inlet line.

Slurry dewatering takes place in the desander, which contains a 20-cm (8-in.) -diameter hydrocyclone operating at a differential pressure of 138 kPa (20 psi) with the flow rate from a single cluster. All process fluids are discharged through the desander overflow for capture and return to the jetting process (closed-loop) or to a drain system (open-loop). The slurry-header flow rate can be controlled by maintaining differential pressure control across the desander.

Separated solids from the desander are collected into the accumulator, which is sized to hold sand from 2 to 4 cluster-discharge batches. The accumulator is a static vessel and, if prefilled with clean water, will provide a bulk cleaning bath that prevents ingress of oil from the desander (Rawlins and Costin 2014). Solids from the accumulator are discharged on the basis of time (i.e., between cluster-discharge batches) or level switch. A vibrating rod or paddle-type level probe accurately provides level-switch notification of solids in a liquid-packed vessel.

Sand concentrate from the accumulator is discharged directly into a collection hopper where the final fluids are removed by gravity for report to the drain system. The collection hopper can be designed as a filter bag or filter bin, depending on the containment requirements. Both systems use the same unit process basis. A filter bag comprises an approximately 1.0-m^3 porous-bulk-solids bag supported by an open frame and is designed to pass liquids while containing sand. This bag is made of high-strength, woven oleophobic material with a multilayer mesh that combines rapid weep of the liquids with high solids retention. The filtrate liquids are drained by gravity into a skid pan and report to the drain system. The filter bin works on the same principle; however, the filter bag is fully enclosed within a recovery bin to capture all liquids and fluids. Both the bin and the bag are reusable once emptied. In addition, the bin or the bag serves as the transport-containment device to bring the dewatered solids to the disposal point. Solids can be removed by a vacuum system, or the entire bin/bag can be sent to a landfill for emptying. Sand separation, collection, dewatering, and transport are accomplished by a combination of gravity, cyclonic, and filtration processes.

Conclusions

Production separators are the first large-volume, low-velocity zone in the crude-oil treating process and will be subject to solids buildup from sand-producing wells. Accumulated sand impairs sustainable hydrocarbon production. Online removal of sand from the production separator improves both facilities uptime and product quality. As water cut grows from field maturation or enhanced oil recovery, the cleaned separator can be pushed to a higher production limit to handle the increased water and associated solids.

All jetting systems, whether jet and pan or cyclonic type, should be designed with the following features:

- Automated spray and evacuation functions to minimize water use, level interference, and operator error.
- Equalized flow rate of spray water (in) and evacuated slurry (out) to prevent level changes within the separator.
- Batch operation within discrete zones along the length of the vessel. Zone sizing allows for a common design for the slurry-handling equipment, simplified scaleup, and commonality in equipment design. Each zone is operated until the outlet slurry concentration reaches 5 wt% solids.
- Properly designed slurry-transport piping, with erosion velocity as the upper limit and particulate-transport velocity (horizontal and vertical) as the lower limit. All slurry-transport piping must be prefilled and post-flushed with clean water to prevent solids plugging.
- Clearly identified final solids-disposal location. This final location must not impede the discharged slurry flow or zone operation.

Cyclonic-jetting technology provides online solids removal by use of a shielded vortex-spray pattern that combines fluidization and evacuation into a single device. Compared with conventional jet and pan technology, this flow profile eliminates disturbance at the oil/water interface, exhibits no wear on the vessel shell, has a simple scaleup design, and consumes less process water. The recommended design parameters for the location of cyclonic-jetting units within a horizontal cylindrical process vessel include the following:

- Use a single row along the centerline for vessels < 2.0 m in diameter and a double row straddling the centerline for vessels > 2.0 m in diameter. Single-row-unit head orientation is vertical, while double-row units are angled at 15° with the evacuation opening pointed toward the centerline.
- Each unit has a set height of 10 cm, spray pressure of 75 kPa, and center/center head spacing of 120 cm.
- The slurry-discharge-flow rate is 30 m^3/h for a four-unit cluster, which is obtained at a differential pressure of 50 kPa. This flow is transported from the vessel in a pipe with a nominal diameter of 5 cm.

Nomenclature

c = empirical constant, varied from 100 to 250
d_p = average particle size, m
D = pipe diameter, m
D_o = overflow discharge orifice diameter, m
D_u = underflow discharge orifice diameter, m
F_L = empirical constant
g = gravitational acceleration, m/s^2
P_i = inlet pressure, kPa
P_o = overflow pressure, kPa
P_u = underflow pressure, kPa
Q_i = intake volumetric flow rate
Q_o = overflow volumetric flow rate
Q_u = underflow volumetric flow rate
s = solid/liquid density ratio, ρ_s/ρ_l, kg/m^3
S = flow split
V_e = fluid erosional velocity, ft/sec
V_{MT} = minimum transport velocity, ft/sec
V_∞ = terminal settling velocity, m/s
μ = fluid viscosity, kg/m·s
ρ_l = density of the fluid, kg/m^3
ρ_m = gas/liquid-mixture density, lbm/ft^3
ρ_s = density of the solid, kg/m^3

References

Ahmad, F., Ward, M., and Fisher, A. 2004. Gecko Wells: Bringing Sand to Surface, A Change in Well Design Philosophy. Presented at the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, Kuala Lumpur, Malaysia, 13–15 September. SPE-87956-MS. http://dx.doi.org/10.2118/87956-MS.

Alexander, J. L. D. 1975. Automatic Discharge Regulator. US Patent Number 3,923,201.

Andrews, J. S., Kjørholt, H., and Jøranson, H. 2005. Production Enhancement From Sand Management Philosophy. A Case Study from Statfjord and Gullfaks. Presented at the SPE European Formation Damage Conference, Sheveningen, The Netherlands, 25–27 May. SPE-94511-MS. http://dx.doi.org/10.2118/94511-MS.

API Publication 421, Monographs on Refinery Environmental Control—Management of Water Discharges: Design and Operation of Oil–Water Separators, first edition. 1990. Washington, D.C.: American Petroleum Institute.

API RP 14E, Recommended Practice for Design and Installation of Offshore Production Platform Piping Systems, fifth edition. 1991. Washington, D. C.: American Petroleum Institute.

Arnold, K. and Stewart, M. 1986. *Surface Production Operations Vol. 1, Design of Oil-Handling Systems and Facilities*. Houston: Gulf Publishing Company.

ASME B31.11, Slurry Transportation Piping Systems, second edition. 2002. West Conshohocken, Pennsylvania: American Society of Mechanical Engineers.

Bretney, E. 1891. Water Purifier. US Patent Number 453,105.

Chin, R. W. 2007. Oil and Gas Separators. In *Petroleum Engineering Handbook, Volume III, Facilities and Construction Engineering*, ed. K. Arnold, Chapter 2, 33–35. Richardson, Texas: SPE.

Coffee, S. D. 2008. New Approach to Sand Removal. Presented at the Offshore Technology Conference, Houston, 5–8 May. OTC-19465-MS. http://dx.doi.org/10.4043/19465-MS.

Fantoft, R., Hendriks, T., and Chin, R. 2004. Compact Subsea Separation System With Integrated Sand Handling. Presented at the Offshore Technology Conference, Houston, 3–6 May. OTC-16412-MS. http://dx.doi.org/10.4043/16412-MS.

Gas Processors Suppliers Association. 2004. *Engineering Data, 12th Edition, Volume 1*. Tulsa, Oklahoma: GPSA.

Geilikman, M. B., Dusseault, M. B., and Dullien, F. A. 1994. Fluids Production Enhancement by Exploiting Sand Production. Presented at the SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA, 17–20 April. SPE-27797-MS. http://dx.doi.org/10.2118/27797-MS.

Govier, G. W. and Aziz, K. 1977. *The Flow of Complex Mixtures in Pipes*. Huntington, New York: R.E. Krieger Publishing Company.

Green, D. W. and Perry, R. H. 2008. *Perry's Chemical Engineers' Handbook,* eighth edition. New York: The McGraw-Hill Companies, Inc.

Jasmani, M. S., Geronimo, E. C., and Chan, L. 2006. Installation of Online Vessel Desander Manifold. Presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, 24–27 September. SPE-101575-MS. http://dx.doi.org/10.2118/101575-MS.

McKay, I., Russ, P. R., and Mohr, J. W. 2008. A Sand Management System for Mature Offshore Production Facilities. Presented at the International Petroleum Technology Conference, Kuala Lumpur, Malaysia, 3–5 December. IPTC-12784-MS. http://dx.doi.org/10.2523/12784-MS.

McLaury, B. S. and Shirazi. S. A. 1999. Generalization of API RP 14E for Erosive Service in Multiphase Production. Presented at the SPE Annual Technical Conference and Exhibition, Houston, 3–6 October. SPE-56812-MS. http://dx.doi.org/10.2118/56812-MS.

NORSOK STANDARD P-100, Process Systems, Rev. 2. 2001. Oslo, Norway: Norwegian Technology Centre.

Plitt, L. R. 1976. A Mathematical Model of the Hydrocyclone Classifier. *CIM Bulletin* **69** (776): 114–123.

Poirier, M. R. 2000. Minimum Velocity Required to Transport Solids Particles from the 2H-Evaporator to the Tank Farm. Report Number WSRC-TR-2000-00263, Westinghouse Savannah River Company, Aiken, South Carolina. http://dx.doi.org/10.2172/764657.

Priestman, G. H., Tippetts, J. R., and Dick, D. R. 1996. The Design and Operation of Oil-Gas Production Separator Desanding Systems. *Chemical Engineering Research & Design* **74** (A2): 166–176.

Rawlins, C. H. 2013. Sand Management Methodologies for Sustained Facilities Operations. Presented at the SPE North Africa Technical Conference and Exhibition, Cairo, Egypt, 15–17 April. SPE-164645-MS. http://dx.doi.org/10.2118/164645-MS.

Rawlins, H. and Costin, J. 2014. Study on the Interaction of a Flooded Core Hydrocyclone (Desander) and Accumulation Chamber for Separation of Solids from Produced Water. Presented at the Produced Water Society Annual Seminar, Houston, 14–16 January. http://www.eprocess-int.com/PWS2014_Rawlins_DesanderStudyR.pdf.

Rawlins, C. H., Staten, S. E., and Wang, I. I. 2000. Design and Installation of a Sand Separation and Handling System for a Gulf of Mexico Oil Production Facility. Presented at the SPE Annual Technical Conference and Exhibition, Dallas, Texas, 1–4 October. SPE-63041-MS. http://dx.doi.org/10.2118/63041-MS.

Shell Global Solutions International (Shell GSI). 2008. Liquid/Liquid and Gas/Liquid/Liquid Separators—Type Selection and Design Rules. Design and Engineering Practive number DEP 31.22.05.12-Gen, Shell Global Solutions International, The Netherlands (January 2008).

Svarovsky, L. 1984. *Hydrocyclones*. Lancaster, Pennsylvania: Technomic Publishing Co.

Tronvoll, J., Dusseault, M. B., Sanfilippo, F. et al. 2001. The Tools of Sand Management. Presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, 30 September–3 October. SPE-71673-MS. http://dx.doi.org/10.2118/71673-MS.

Wilson, K. C., Addie, G. R., Sellgren, A. et al. 2006. *Slurry Transport Using Centrifugal Pumps,* third edition. New York, New York: Springer.

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