Study on the Interaction of a Flooded Core Hydrocyclone (Desander) and Accumulation Chamber for Separation of Solids from Produced Water

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Presented at the 2014 Produced Water Society annual seminar, January 14-16, Houston, TX.

Abstract

The flooded core solid-liquid hydrocyclone, termed a desander, is used extensively in the oil and gas industry to separate sand and solids from produced water. A desander comprises a standard solid-liquid hydrocyclone with an accumulation chamber connected to the apex. The accumulation chamber prevents formation of an air core. Thus, the hydrocyclone operates fully flooded. Solids collect in the accumulator for intermittent removal, while the overflow is continually discharged. In this manner the desander operates as a separation, and not a classification, device. With a flooded core and static volume of water in the accumulator, the sand particle trajectory from inlet to apex is modified compared to the standard open underflow hydrocyclone classifier. This project investigated the desander performance and the interaction between the hydrocyclone and accumulator with emphasis on particle travel. Laboratory testing of a desander and hydrocyclone of identical geometry showed no difference in hydraulic capacity and the same measured cut size (D_{50}). Settling of solids to the accumulator does not follow a Stokes Law relationship, and the measured apex flux rate limits the inlet solids concentration to ~2000 ppmw at normal conditions for small diameter desanders.

Produced Water Solids Removal

Sand and solids are present in produced water in all production systems (Rawlins, 2013a). Sand reports to the production system from producing wells, whereupon it settles in the low velocity zones of separator and free water knock out (FWKO) vessels. Sand that fills these vessels is commonly removed by jetting or manual cleaning operations. Intermediate size sand, typically 25-200 microns in diameter, may flow with the water phase to exit the production separators (Rawlins, 2013b). Small solids <25 microns generally collect in the oil phase or at the rag layer where they form part of the basic sediment & water (BS&W) in the oil product. Large solids >200 microns tend to collect and fill the separating vessels. These intermediate solids that discharge with the water phase will interfere with produced water treatment by eroding control valves, plugging and eroding deoiling hydrocyclones, filling flotation cells, plugging media and cartridge filters, contributing to oil-in-water values (due to oil coating), or interfering with water injection systems. Desanding hydrocyclones, shown in Figure 1, are the most common method for primary intermediate solids removal from produced water systems.

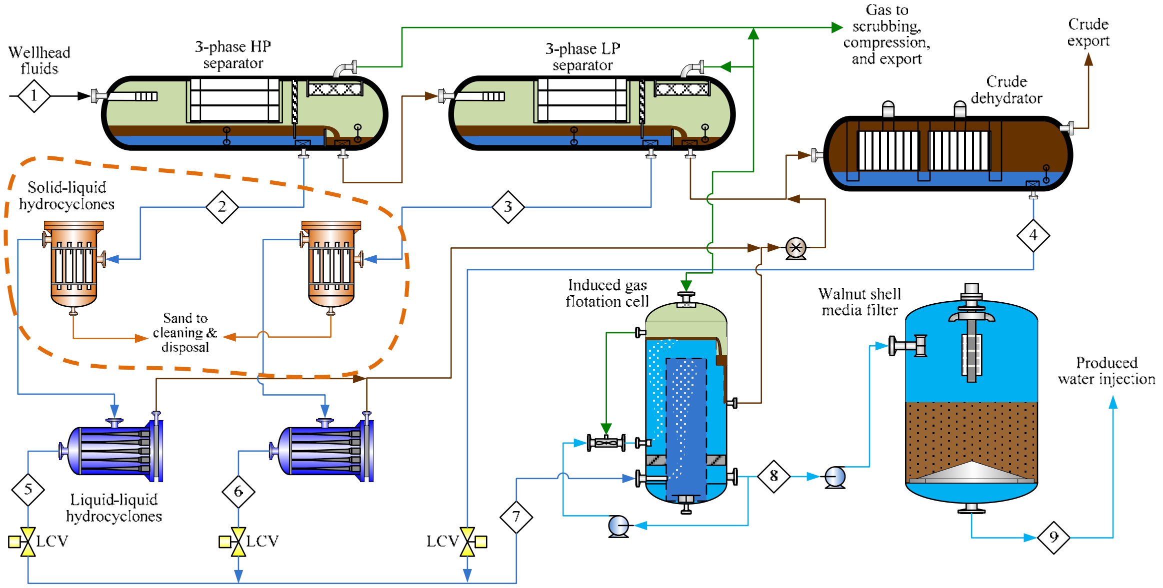


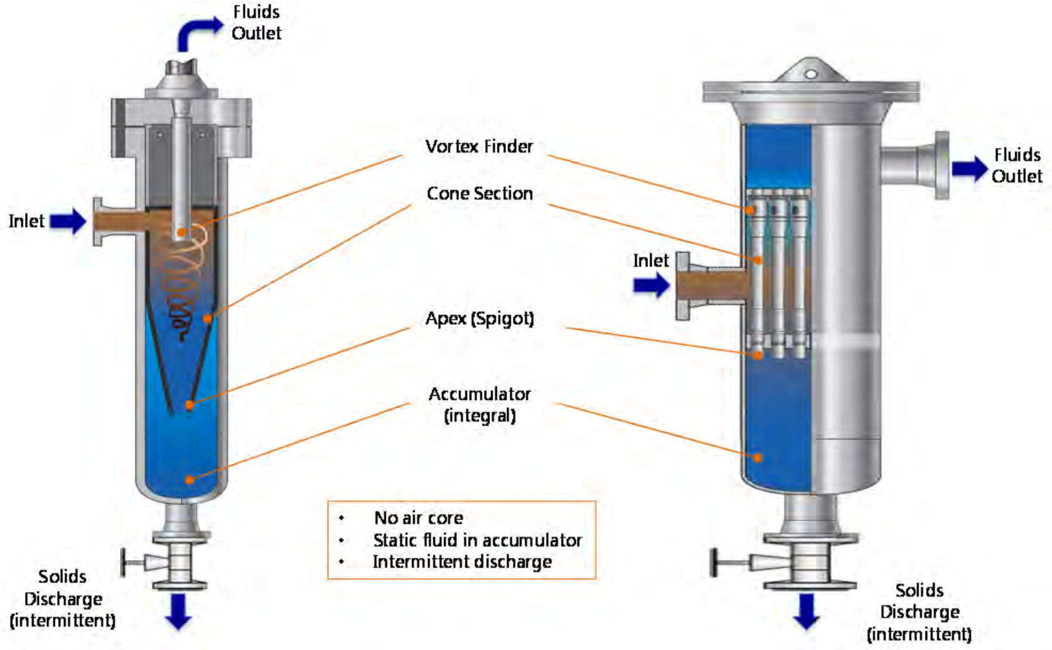
Figure 1. Process flow schematic of well fluid separation system with emphasis on produced water treatment. Dashed encircled area shows location of desanding hydrocylones (desander) used to remove sand and solids prior to oil removal. Typical produced water desander handles 100-500 ppmw solids at 25-200 micron particle size.

Desanding hydrocyclones, also called desanders, are located directly on the water outlet of a three phase separator or FWKO. They should be located upstream of deoiling hydrocyclones and the liquid level control valve (Ditria and Hoyack, 1994). The produced water at this point will generally have a sand concentration of <100 ppmw. The solids particle size will range from 25-200 microns, with 125 microns as the common mean. Desanders operate using the inherent pressure in the produced water stream and will require 10-30 psi of differential pressure. They are a static device with no moving parts and have replaceable wear components. Locating the desander as the primary treatment on the produced water stream will protect all downstream components and will have no negative effect on subsequent oil removal from produced water.

Desander and Accumulator

Desanders are a cyclonic device, which is a common unit process in the upstream oil and gas industry. Cyclones are used for gas-liquid separation (separator internals, gas scrubbing, and compact separators), liquid-liquid separation (deoiling hydrocyclones), and solid-fluid separation (wellhead desanders and produced water desanders). Cyclonic technology uses pressure differential to drive the phase separation and relies on the geometric shape of the unit to create the desired flow pattern. Cyclonic technology has the highest throughput-to-size ratio of any separating device (Rawlins and Wang, 2000). For a given flow rate it will have the smallest footprint and weight of any technology, which is an advantage in offshore and subsea systems. In addition, cyclonic devices are unaffected by facility motion (necessary on floating systems) or orientation. Due to the vortex flow pattern, a cyclonic device will generate between 100 and 5,000 times the acceleration due to gravity (g-forces) pending the diameter and pressure drop.

Desanding hydrocyclones are designed specifically for solids removal from a liquid stream. Two styles of desanders have found use in the upstream petroleum industry. Figure 2 shows the single cone versus the multi-cone style. Both styles are made from a pressure vessel housing containing one or more cyclonic inserts or lines. The insert style has a single cyclonic replaceable insert while the multi-cone has multiple cyclonic liners operating in parallel. The insert and liner are each replaceable within the vessel and are designed to provide the cyclonic separation flow pattern and contain the solids erosion. The pressure vessel contains the operating conditions but sees no erosive flow. Both styles have an inlet connection, clean water fluids outlet, and integral accumulation chamber (accumulator) for collection and periodic discharge of the separated solids.



Insert Style (Single Cone)	Liner Style (Multi-Cone)
One insert per vessel	Many liners per vessel
Multiphase flow	Liquid only flow
Smaller diameter vessel	Larger diameter vessel
Change insert size for turndown >3:1	Change qty. of liners for turndown >3:1
No fluid partitioning	Unequal multiphase fluid partitioning
Can treat particles 1”-2” diameter	Can treat particles 0.1”-0.2” diameter
Inlet solids concentration to 5 wt.% or higher	Inlet solids concentration to 0.25 wt.%

Figure 2. Cross section schematics of two styles of desanding vessels – insert style (left) and liner style (right). The table below the drawings lists the attributes and operating range for each style.

Figure 2 lists the attributes and operating range for each style of desander. The primary operating difference is how the incoming fluids are treated. For the single cone, all fluids are contained within the one cyclonic insert. Incoming fluids to the multi-cone style are dispersed within the inlet chamber and have to distribute to each individual cyclonic liner. In using a desander for multiphase applications (i.e., wellhead desander), the multi-cone style does not distribute the gas and liquid phases equally to each liner. Therefore, variable performance can be exhibited. The single cone style treats multiphase fluid in one device without gas-liquid portioning and provides higher separation efficiency. The insert style is used for multiphase desanding, whereas the multi-cone style is preferred for liquid-only desanding.

One of the features of cyclonic devices is that as the diameter decreases, so does the separating size. For a liquid-only application, a separation size of 10 microns is exhibited with a 1.5” diameter cyclone, whereas a 3” and 10” cyclone will have a 30 micron and 60 micron separation size respectively. Multi-cone desanders are preferred for liquid-only applications due to the higher solids removal efficiency. Single cone desanders work well in multiphase flow where the incoming fluid is a mixture of gas and liquid. Thus, the continuous phase fluid has low viscosity and density, and particles are easy to remove. A 10” insert desander in 95% gas void fraction (GVF) stream can achieve a separation size of less than 10 microns.

Multi-cone desanders have higher solids removal efficiency in liquid applications; however, they are limited in the particle size they can treat without plugging. The liners in a multi-cone application may have a 0.25”-0.5” critical orifice diameter (either inlet width or apex diameter), and particles exceeding this size will plug the liner units, which requires removal of the liner to remove the blockage. Insert style desanders accommodate particles up to 1”-2” in diameter. These size particles are not commonly seen in produced water streams, but are present in raw well flow. Hence, single cone desanders are used in wellhead applications.

Desanders were originally developed for treating water well flow in agricultural regions to prevent sand particles from plugging irrigation nozzles. These applications had low concentrations of sand (<10 ppmw). Desanders were then introduced to the upstream oil industry in the 1960s for produced water treatment, and the concentration of sand exhibited was much higher than envisioned from the agricultural units. A general rule of thumb for the maximum inlet solids concentration a desander could handle was one percent by volume. This value worked sufficiently in large diameter desanders, but as the liner style desanders became more prevalent and the cyclonic diameters decreased to 3”, 2”, and 1”, the 1% value showed problems of plugging and premature wear failure in many applications. A more accurate maximum value was required, especially a method that could be used across a range of operating conditions and cyclone diameters. The present work was undertaken to measure the maximum inlet concentration small diameter cyclones could treat and determine a sizing method to apply to the range of desander diameters.

Operation of Flooded Core Hydrocyclones

The solid-liquid hydrocyclone was developed in the 1890s and finds primary use in the mineral processing industry. Grinding of ore to liberate valuable minerals uses banks of hydrocyclones (typically 10”-40” in diameter) as a classifying device in closed-circuit arrangement. These hydrocyclones are operated at low pressure (inlet <30 psi) with open underflow and overflow discharge (e.g., atmospheric pressure) and process slurry streams with 20-40 wt.% solids. The underflow fraction containing coarse solids is returned to the mill inlet for further grinding, while the overflow stream contains the fine solids fraction that is sent to downstream processing (typically for flotation or further attrition). The key aspect in comparing a mining or open underflow hydrocyclone to a desander is the treatment of the underflow stream, as illustrated in Figure 3.

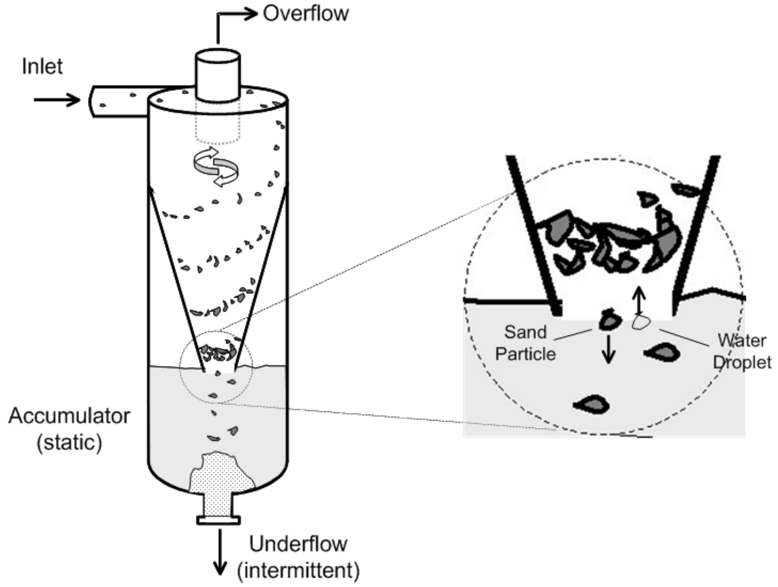


Figure 3. Schematic of single-cone desander showing solid-fluid volume swapping that occurs as particles discharge through the apex and enter the accumulation chamber.

A mineral hydrocyclone has an open underflow stream discharging at atmospheric pressure. The concentrated discharge slurry discharges continuously and collects into an open launder or trough. A desander has a fully enclosed underflow stream where the solids are collected into an accumulator chamber that fully encapsulates the underflow orifice, and solids are discharged intermittently from the system. The solids in a desander are concentrated as they spin down the length of the cone and exit the apex into the accumulation chamber. The accumulation chamber is a static body of water and the solids exiting the apex displace the accumulator water, which then has to return through the apex into the cyclone body to eventually discharge through the overflow. This effect is illustrated in the circled area of Figure 3.

The volume of solids (sand) entering the accumulation chamber displaces an equal volume of water back through the apex, which can be termed volume-swapping (Rawlins, 2002). Volume-swapping occurs due to density differential between the solids and water. While the particle "falls" into the accumulator, the downward trajectory of the particle is slightly opposed by the upward flow of the water, which reduces the net terminal velocity. At low solids concentrations the terminal velocity reduction is negligible; however, as the concentration of solids discharging the apex increases, the amount of liquid returning will eventually choke the downward solids flow. Therefore, a maximum flux exists at which the desander can operate. Above the flux limit, solids will start to aggregate at the apex entrance and back up into the cone section. This effect is illustrated in Figure 4. As the solids level rises in the cone section, eventually the cyclonic body becomes full and the solids will report to the vortex finder, resulting in degradation of separation performance. Laboratory investigation has shown that filling of the cyclonic body in 2" diameter desanders can happen in a few minutes.

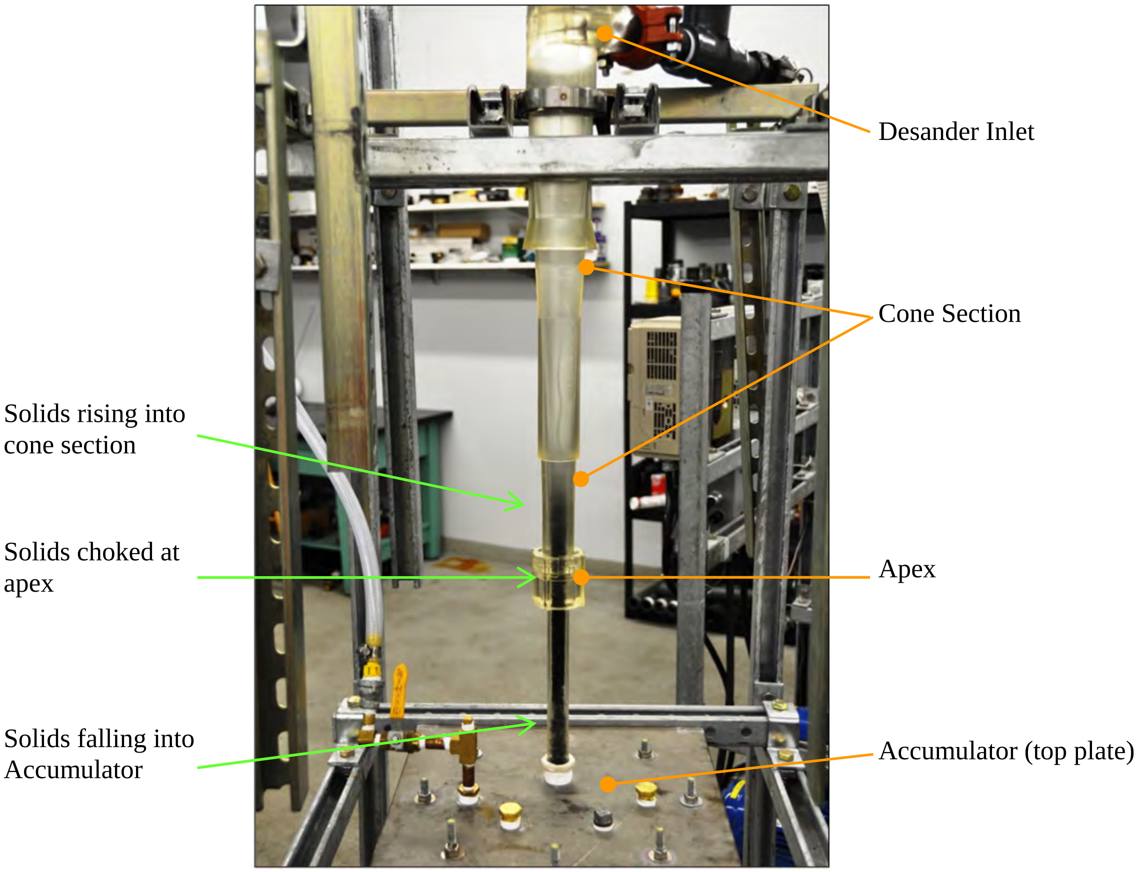


Figure 4. Two inch clear hydrocyclone configured as a desander with large accumulator vessel. The unit is operating at 20 psi pressure drop and processing 12/20 mesh coal particles. The particles have exceeded the apex flux limit and are collecting in the lower cone section. Eventually the level of solids will rise to the vortex finder, resulting in degradation of separation performance.

Another effect of aggregated solids collecting above a choked apex is premature erosive failure in the cone section of the cyclonic component. A high velocity spinning fluidized bed of solids exists above the apex choke point. This concentrated rotating fluidized bed generally erodes the middle section of the cone as shown in Figure 5. The 1.5" diameter desander in this photo experienced premature failure in the cone section due to choking of the apex. The solids trapped in the cone section were too heavy to report to the overflow, but were unable to quickly pass through the apex into the accumulator. These spinning solids eroded the cone section until the wall was breached.

Figure 5. Erosion pattern marks on a 1.5" diameter desander showing premature failure in the cone section due to choked apex. Solids trajectory is from left to right. The cone section (left) shows severe wear while the apex (right) shows little or no erosion.

Studies on Flooded Core Hydrocyclones

Operating a standard hydrocyclone with open underflow results in a central air-core that exists throughout the full length of the cyclonic body (from apex to vortex finder) and has a slight negative pressure (Svarovsky, 1984). Encapsulating the apex orifice floods the cyclonic body and prevents the formation of an air-core. The majority of scientific literature on hydrocyclone operation and modeling pertains to open-underflow design containing an air-core (Plitt, 1984). A few studies have been conducted with a flooded-core, solid-liquid hydrocyclone; however, none of these were conducted with a static accumulation chamber. Researchers at McMaster University studied the velocity distribution in a 3" glass hydrocyclone operating without an air core (Knowles et al., 1973). They connected the underflow to a pipe network that encapsulated the apex. However, the system was operated by continuously pulling fluid away from the underflow, and thus preventing a static fluid chamber. The operating conditions were set such that the underflow and overflow streams had similar flow rates. Only velocity profiles were measured using tracer particles and high-speed photography, and the tangential, vertical, and radial profiles were similar to an open underflow hydrocyclone. The tangential velocities were found to be less than half compared to operation with an air-core. Further research was conducted with the same setup, but varied the underflow/overflow split and measured classification performance (Witbeck and Woods, 1984). Their results showed a less sharp (flatter) classification curve with the flooded hydrocyclone and a pressure drop of 4-7 times compared to open underflow (note: the current body of work showed negligible difference in pressure drop when comparing open and flooded underflow). Researchers at Northeast University of Technology (Shenyang) measured performance of 2" and 3" water-sealed hydrocyclones (Quian et al., 1989). Similar to the McMaster work, they withdrew a liquid stream from the underflow chamber, which negated a static bed of water. When compared to open underflow performance, they measured slightly greater solids recovery and a 1.6 times increase in pressure drop. When enclosing the underflow stream, they increased the apex diameter by 10 times to minimize blockage potential. All of these studies removed the air core by encapsulating the underflow stream; however, they negated the development of a static bed by withdrawing fluid continuously away from the accumulation chamber.

Experimental Flow Loop

The primary goal of this research was to determine the maximum flux rate, as a function of inlet stream solids concentration, which a desander could process. To study the interaction of a flooded core hydrocyclone (desander) and static accumulation chamber during separation of solids from water, an experimental flow loop was built. Figure 6 shows a photograph of the test loop with primary components identified. A 60 gallon cone bottom tank was used to house the inlet stream. Solids were added to the tank via a vibratory feeder and the slurry was prepared using a pneumatic tank mixer. Inlet concentrations to 100 ppmw accuracy were able to be prepared. The feed stream was delivered at the desired pressure/flow using a centrifugal pump with variable frequency drive. Inlet pressure to the test hydrocyclone/desander was measured using a pressure indicator (0-30 psig). Overflow from the hydrocyclone/desander was returned at atmospheric pressure to the mixing tank, making a closed-circuit test loop. The test cyclonic device consisted of a 2" diameter clear urethane (commercial) hydrocyclone connected to a 2" clear cylindrical accumulation chamber (24" length with 10 ml gradation marks). The hydrocyclone had a 0.25 in^2 inlet area, 0.8 inch diameter vortex finder, and 0.625 inch diameter apex.

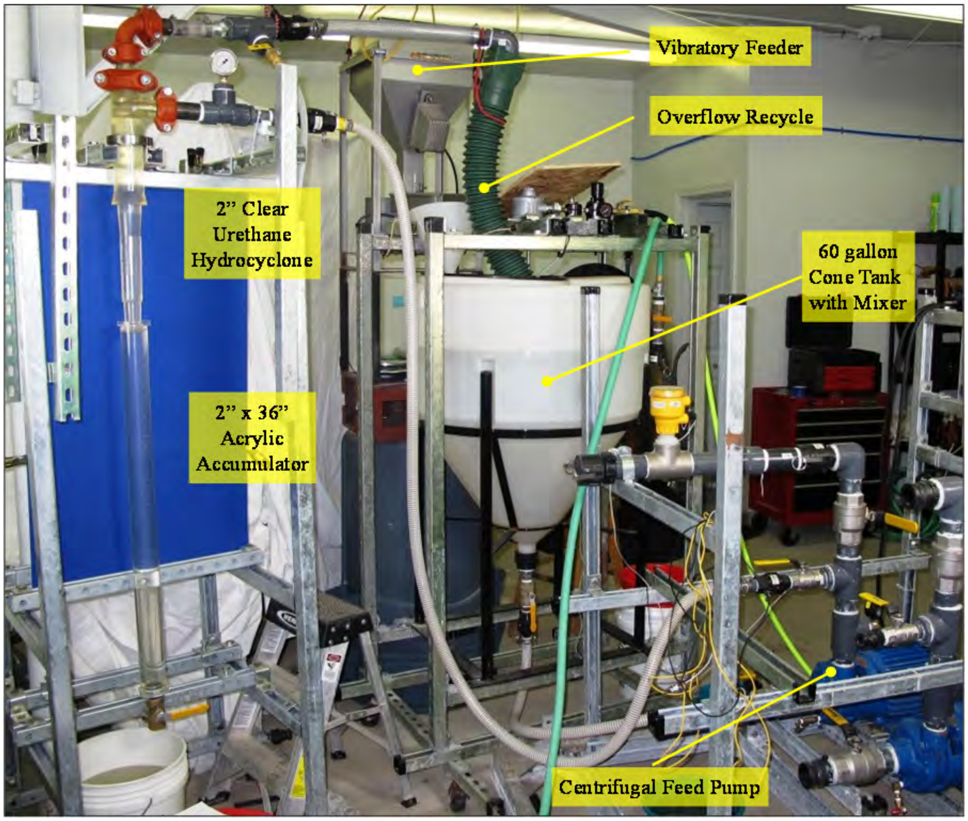


Figure 6. Experimental flow loop setup for testing hydrocyclone/desander apex flux rate. The loop consists of 60 gallon cone-tank with mixer, centrifugal feed pump, and 2" clear hydrocyclone with graduated accumulator.

The test slurry consisted of municipal water (1.007 s.g. and 1.014 cP at 15°C) mixed with SiO_2 test sand. Most of the tests used silica sand with a 2.66 s.g. and particle size from 38-600 µm in diameter. The <38µm fraction was removed by wet sieve. For tests using finer sand, a monocrystalline silica was used with a P_{50} of 12 µm and 95% passing 45 µm. This material had a 2.66 s.g. as well. The coarse sand had a packing void fraction of 47.3%, while the fine sand had a value of 44.4%. Densities were measured using immersion pycnometry, void fraction by volumetric analysis, and viscosity by capillary viscometer.

In preparation for the test work, a hypothetical model was developed based on the following premises:

- All solids entering the hydrocyclone report to the apex (i.e., the solids used in testing were large enough to represent 100% recovery). This premise was necessary to test a simple mass balance inlet concentration measured without subtraction of particles reporting to the overflow.
- Particles entering the hydrocyclone travel in a standard vortex pattern from the inlet to the apex.
- Upon reaching the apex, particle motion and velocity are fully arrested because the liquid in the accumulator is static.
- The particles fall through the static liquid in the accumulator as approximated by Stokes' Law. Based on this premise, the apex threshold concentration should be a function of particle size, solid-fluid density, and liquid viscosity.
- For every volume of particle that enters the accumulator, an equivalent volume of liquid returns upward through the apex to eventually exit with the hydrocyclone overflow stream.
- The apex represents a choke point in the downward flow of particles from the hydrocyclone to the accumulator. As such, once the choke value (or apex threshold) is reached, the rate at which the particles fall from the choked apex should remain constant. Further increase in inlet concentration would result in continued deterioration of hydrocyclone separation efficiency, as defined by mass balance, because more particles cannot be pushed through the choked apex and will then report to the overflow stream.
- A model was constructed to provide a first-order estimate of the target concentration.

The general test procedure first used the theoretical inlet concentration based on the target particle size range. A particle size range (i.e., 106-212 µm) was used in each test with the geometric average used as the indicative size. This value was used to set the vibratory feeder rate (g/min), which would provide the desired inlet concentration in ppmw. Flow was established through the loop such that the desander exhibited a 20 psi pressure drop (~22 gpm). The vibratory feeder and tank mixer were started along with test time. Slurry was formed in the tank and allowed to reach steady-state through the loop. Solids fed through the hydrocyclone inlet and traveled in a vortex pattern to the apex. Visual confirmation was used to confirm steady-state particle travel, as shown in Figure 7.

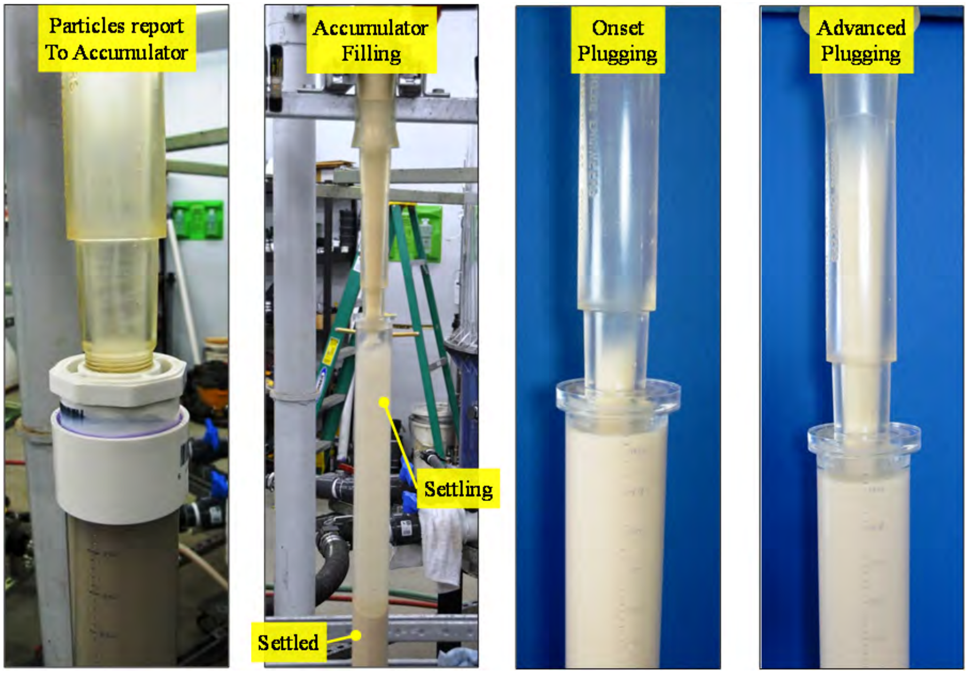


Figure 7. Photographs showing (left to right) particle travel through hydrocyclone cone section to accumulator, particles settling and settled in accumulator, onset of apex plugging, and advanced plugging where solids begin to fill up hydrocyclone body.

The time to fill two 400 ml sections of the accumulator was recorded. In addition, visual assessment of the solids level at the cone-apex interface was recorded. If hydrocyclone appeared to be filling at seven minutes (Figure 7 right), the test was allowed to run at least three more minutes before it was shut down. The inlet concentration was deemed above the apex threshold. If the hydrocyclone was not filled by 10 minutes, the test was completed and the inlet concentration was deemed below the threshold. If the test conditions were below apex threshold, the concentration was increased for the next run or vice versa if the conditions were above apex threshold. At the end of each test, the collected solids were dried and weighed. An iterative approach was taken until the apex threshold was bracketed by 100 ppmw concentration. For example, at 106-212 particle size range, 2600 ppmw inlet concentration was below the apex threshold while 2700 ppmw inlet concentration was above the apex threshold. Therefore, the apex threshold was set at the average concentration of 2650 ppmw.

Apex Solids Threshold

Data for apex solids threshold at five particle size range averages is shown in Figure 8. The geometric average for each particle size range was used as the mean size listed on the abscissa. The ordinate axis lists the inlet solids concentration (ppmw) required to reach the apex threshold. The actual data curve shows the limiting line of operation below which the desander operates with steady-state transfer of solids from the cyclone through the apex to the accumulator. Above this curve the hydrocyclone body will fill with solids due to apex choking, and the rate of filling is proportional to the distance operated above this curve. The particles shown on the curve have the same mineralogy and specific gravity at all particle sizes.

Also shown in Figure 8 is the first-order particle transfer model based on Stokes' settling theory. This line is based on the premise that the average particle size settles unhindered to terminal velocity based on Stokes' Law. Stokes shows the settling velocity proportional to the square of the particle size; therefore, larger particles will fall through the apex faster, which results in higher inlet concentrations allowed at the desander inlet. The actual data has nearly an inverse square relationship between particle size and inlet concentration showing impediment during settling. This reduction in velocity is due to both the upward flow of liquid from the accumulator through the cone section and crowding of the particles at the apex resulting in packed, not free, flow. A second order model encompassing these parameters is being developed to more accurately scale this effect based on mechanistic principles.

Part of the test program measured the rate of solids collection in the accumulator using the 10 ml graduation marks. The collection rate (ml/s converted to g/s using packing void fraction and density) was determined prior to, during, and after reaching the apex threshold rate. Figure 9 shows the results for sand in the 106-212 µm size range. The x axis lists the percent of apex threshold rate, which had been previously determined for this sand size range. The y axis lists the apex flux rate in g/s. The apex flux rate steadily increases to a maximum of 3.3 g/s at 100% threshold rate, then slightly declines to a near steady 3.0 g/s above the threshold. Solids are passing through the apex at all inlet concentration levels, but the flux rate through the apex reaches a maximum point (3.0 g/s in this case). Above this flux rate, the solids will start to fill the cone section. The maximum apex flux rate can be used to determine the maximum allowable inlet concentration for operation without filling the cyclone body.

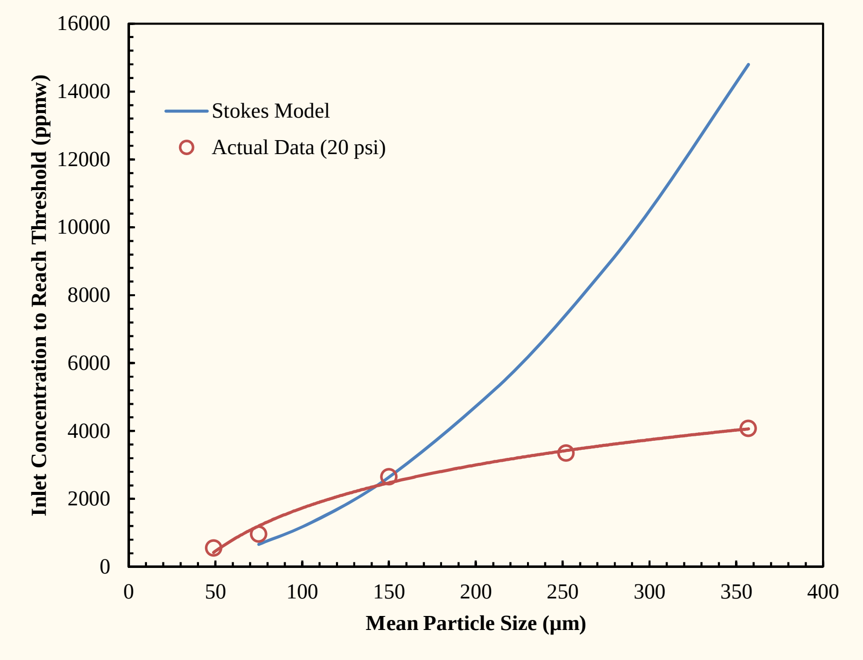


Figure 8. Comparison of Stokes' Law based settling model versus actual data from apex solids threshold testing.

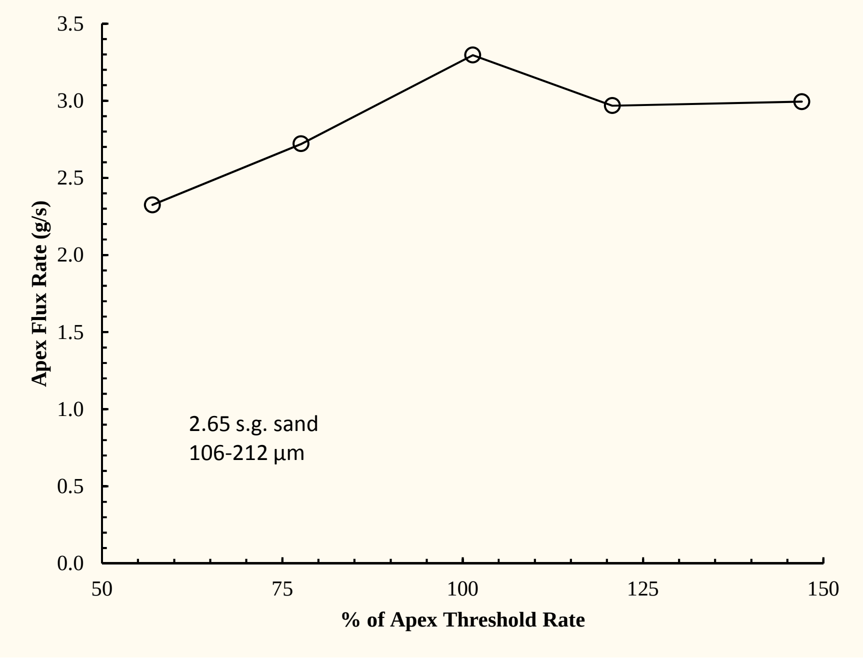


Figure 9. Apex flux rate as a function of percent of threshold rate. After reaching a functional threshold, the flux rate settles to a constant value.

The maximum flux rate at 100% apex threshold was determined for a range of sand particle sizes and this data was used to generate a series of curves for first-order (approximation) scaling to other desander sizes. Figure 10 shows the mean particle size versus inlet threshold concentration (ppmw) for 2"-8" desanders. The desanders are scaled up using common cyclonic geometry ratio (D_{apex}~$0.3D_{cylinder}$). For example, a 3" desander separating sand from water with 125 μm mean particle size has a limiting inlet value of ~2000 ppmw at the inlet stream before the apex is choked due to overcrowding. An 8" desander has a limiting value of nearly three times that rate (~6000 ppmw). These curves provide a more accurate guideline than the 1% (10,000 ppm) rule of thumb commonly used. They also show that small diameter desanders should not be used in high solids concentration applications like treating sand jet slurry or during well flow back operations.

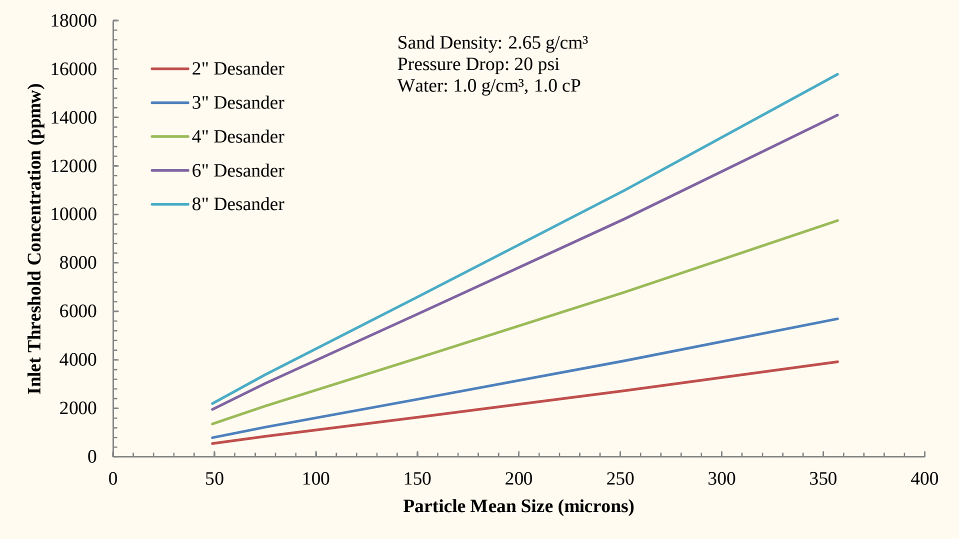


Figure 10. Curves showing inlet concentration at which apex threshold is reached for various diameter desanders. Values based on sand in fresh water.

Apex Flux Balancing

The curves in Figure 10 show the limiting inlet concentration that a specific size desander can operate before apex choking occurs. This data is generated and modeled for a static accumulator in which the liquid is displaced up by the downward falling particles. Modifying the system design to allow the liquid in the accumulator to exit the contained volume in a manner other than upward through the apex will increase the downward flux of particle, thus enabling operation of a desander with a much higher inlet concentration. An apex flux balance line is installed from the accumulator chamber to an external location with lower pressure. The outward liquid flow is controlled and the minimum amount should be equal to the volume rate of solids entering from the apex. The liquid is removed at the same rate as the solids are coming in. This method, called Apex Flux Balancing (AFB), can be used to overcome the threshold induced by a static accumulator. Figure 11 illustrates a flow schematic for a single cone desander with an AFB line installed.

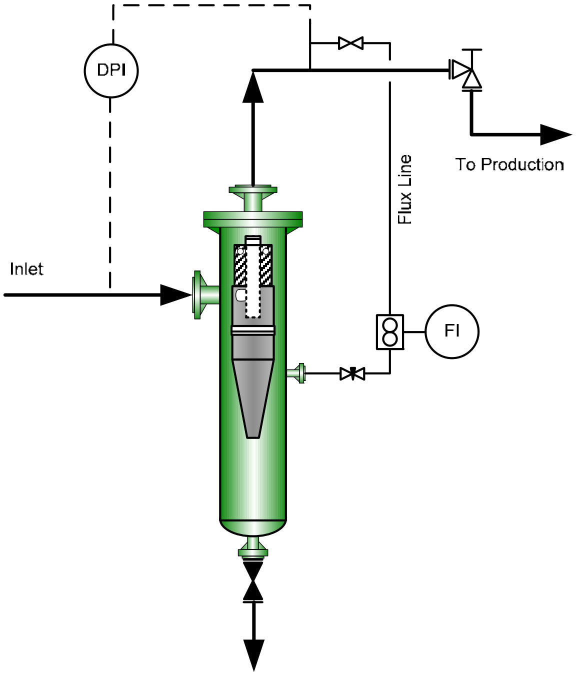


Figure 11. Flow schematic of single cone desander with apex flux balance line installed. Connection is made to the desander vessel body, above the apex, to the overflow stream. A manual control valve and flow indicator are used to balance the liquid removal rate with incoming solids collection rate.

The flux line inlet is connected to the desander vessel body and the take-off point is above the insert apex (which creates a tortuous path and prevents solids from being pulled into the balance line flow). The outlet of the balance line is connected to the overflow stream in this case, which provides a manageable lower pressure connection point. The flow through this line is controlled using a manual valve and flow meter indicator. Ideally, the line, valve, and flow meter are sized to allow removal of liquid in a controlled manner equal to the amount of solids entering the lower accumulator section. This same configuration can be used with the liner style desander, with the take-off point from the top section of the lower chamber. In cases of a secondary or external accumulator, the flux line can be attached to the top of this lower vessel, but should be designed to minimize solids capture by the balance line fluid flow.

Conclusions

The desander, a flooded-core solid-liquid hydrocyclone, is a simple device with a complex fluid flow pattern. The separation and hydraulic characteristics follow the well-established principles of a hydrocyclone unit process. The transfer of the separated solids into the accumulation chamber (both integral and secondary) does not follow a simple Stokes relationship. Laboratory analysis of particle trajectory measured the flux rate of these particles and the effect of solid-liquid volume-swapping to yield the apex threshold value. The apex threshold value limits the separation efficiency independent of the cyclonic factors of the unit process. Along with fluid properties and proper process boundary conditions, knowing the characteristics of the inlet solids (particle size and concentration) is critical to prevent process inefficiencies that may degrade separation performance or lead to early mechanical (erosive) failure. The concentration of solids that a desander can treat has a defined value based on particle size and fluid properties, and for small diameter desanders is less than the common guidelines used in the industry. A small diameter desander (<4”) should not be used in high solids concentration applications such as sand jetting or well testing and clean-up.

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