Application of Multiphase Desander Technology to Oil and Gas Production

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Presented at the 3rd International Conference on Multiphase Technology in Banff, Alberta, Canada: 3-5 June 2002.

1 ABSTRACT

Solid-liquid hydrocyclone technology has matured to encompass multiphase flow applications. Multiphase desanders were first employed by the oil industry in 1995 to remove solids upstream of the wellhead choke[1]. The technology has primarily advanced based on field applications, with little testing or modeling. This paper will provide a background of multiphase desanding and its applications, and summarize the work accomplished to date on modeling pressure drop and separation efficiency. An outline of an empirical model for scaling multiphase desanders from liquid based applications is presented as work to be undertaken in a multiphase flow loop. Comparison to the existing hydraulic and pneumatic cyclone mechanistic models is also discussed.

2 INTRODUCTION

2.1 Oil and Gas Solids Control

All oil and gas wells produce solids in varying concentration with the produced fluids. These solids originate either from the reservoir, such as sand, clay, or silt, or may be corrosion byproducts from the downhole equipment. Produced solids are normally smaller than 250 micron in diameter and are found in varying amounts, with a typical concentration range of 5 to 250 PPM[2].

Production of sand from oil & gas wells is a common difficulty for processing facilities, and is often caused by unconsolidated reservoirs, high water production rates, or the failure of gravel packs and other sand control measures. Detrimental effects of sand production include mechanical damage (erosion) to chokes, flow lines, control valves, pumps and other high velocity areas, reduced residence time (in the case of separators) or partial blockage of pipelines, and high environmental discharge costs.

The main sand control solutions to date have been to cut back fluid production rates to reduce the rate of sand, work over of wells to repair or install gravel packing or screens, or increased equipment maintenance which leads to reduced plant availability. The need for an alternative solution that enhances rather than restricts production was recognized by operators, which lead to the introduction of multiphase desanders in the mid 1990's. This device enables a producing operation to remove solids on-line at the wellhead choke, which both maintained production while protecting process equipment.

Selection of the proper solids removal location is primarily a matter of economics. The four principal solids removal locations identified for a common separation train are shown in Figure 1. Solids removed upstream of the wellhead choke will protect all downstream process equipment, while removal after the choke will protect the separation processes but not the choke. The determining factor on desander location is the cost balance of an upstream (high pressure) separating device with the cost of choke maintenance. Post-choke removal has a lower design pressure (lower cost), but the equipment may be larger due to the increased actual volume of gas treated. Alternatively the production separator (2 or 3 phase) makes a great separation device for solids, however solids build up decreases residence time. A sand jet system can be employed to remove collected solids in the vessel, but does not benefit downstream oil or water treating equipment. Many standard (liquid only) desander systems installed on water and oil treating lines do an excellent job of protecting treaters and flotation cells from filling up or preventing injection wells from plugging. The aim of this paper is to discuss the removal of solids in multiphase applications, before or after the production choke.

A serendipitous benefit of removing solids early in the process scheme is the cleanliness of the separated sand. Upon commissioning of the first commercial wellhead desander, one of the major concerns of the operator pertained to solids handling. This concern was placated when the sand dumped from the accumulator was found to be relatively free of hydrocarbons (clean enough for direct discharge). The reasons for the low hydrocarbon concentration on sand are twofold. First, sand is typically (and preferably) water wet in the reservoir, and will remain so unless allowed to "cook" in production separators for extended periods. During retention in process vessels the sand is subjected to interfacial modifying chemicals and processes that allow the solids to become oil wet, thereby creating an oil layer on the sand particle. Removing the sand ahead of the separators prevents oil adsorption. Second, proper operation of a multiphase desander ensures that the collection vessel (accumulator) is pre-filled with clean water after each purge cycle. Therefore the separated sand is allowed to sit in a clean water environment as hydrocarbon well fluids are prevented from entering the accumulator to discharge with the sand. In field applications typical total hydrocarbon concentration on sand has measured less than 0.5% by weight (kg oil per kg dry sand). This is analogous to oil on drill cuttings, which can be directly discharged in many regions, providing the oil on solids concentration is less than 1% by weight.

3 DESANDING HYDROCYCLONES

3.1 Desanders as Subset of Hydrocyclones

Solid-liquid cyclones (hydrocyclones) have been used for many decades in various industrial applications ranging from classification of mineral solids to removing grit from hot tomato catsup. In the oil and gas industry solid-liquid cyclones are used in drilling operations, while only recently has this technology found significant use in oil and gas production operations[2].

By definition, a "desander" is a solid-liquid hydrocyclone that operates with an enclosed underflow and an accumulation section (integral or separate) with a batch discharge, as shown in Figure 2. They are also called water-sealed hydrocyclones or grit separators. Solids are centrifugally separated from the liquid as per a standard hydrocyclone, however they are not continuously discharged from the apex (spigot). Solids exiting the apex collect into a closed accumulation section for batch discharge. The rate of discharge is directly proportional to the rate of solids recovery and the size of the accumulation vessel. Because of batch discharge, desanders should be limited to cases where solids are 1 vol.% or less. When the concentration of the solids is significantly larger than this amount the application would be better suited for a standard hydrocyclone with open underflow.

Closing the underflow allows use in high-pressure operations and prevents air from being drawing into the vortex center. With a desander all fluids entering the unit, are discharged from the overflow, as no liquid split occurs. Because the underflow is closed, the pressure drop is controlled from inlet-overflow. Throttling of this stream controls the pressure drop, and in effect the desander acts as an orifice in the line, regardless of the operating pressure. Desanders have been built for 10,000# API rating (68,900 kPag), while standard hydrocyclones have been generally limited to 100 psig (689 kPag). Additionally, since the underflow is closed no air core is formed in the center of the vortex. In open underflow hydrocyclones the vortex flow pattern creates a low-pressure region at the cyclone center, which draws air through the apex up into the vortex finder. Air mixed with hydrocarbons is a hazardous mixture, and closing the underflow prevents this from occurring. Closing the underflow does have the effect of coarsening the separation size but increasing the sharpness of separation. This occurs by limiting the settling velocity of small solids, but this effect has not been quantified and will be investigated in future analysis[3].

Desanders are available in different sizes and styles. The vessel style and liner style are shown in Figure 2. These units vary in size range and construction, and selection of each is dependent upon the capacity, separation size, and turndown requirements. The vessel size ranges from 2-30 inch nominal diameter (50-750 mm), with the vessel itself acting as the desander. The liner style ranges from 0.5-4.0 inch nominal diameter (10-100 mm), and consists of a pressure vessel with several "liners" contained within. The vessel style units are used in applications requiring large flow rates and coarse separation size (25-200 microns), while the liner style is used in applications at most any flow rate with fine separation size (10-50 microns).

Like all cyclonic devices, desanders offer the highest throughput-to-size ratio compared to conventional separation equipment, such as plate interceptors or filters. Their weight and size is usually 25% of standard equipment, and the capital cost is likewise much lower. Desanders require little, if any, operator interaction for operation, and due to the fact they have no moving parts maintenance is minimal.

3.2 Desander Models

Solid-liquid hydrocyclones have been studied extensively because of their applicability in separation processes, however desanders specifically have received little attention. Researchers such as Yoshioka & Hotta[4], Bradley[5], Rietema[6], Holland-Batt[7], Trawinksi[8], Plitt[9], and Svarovsky[3] have provided a good base of mechanistic and empirical models to draw upon, but their work is primarily based on open underflow hydrocyclones used in classification applications. Some work has been added by each in terms of underflow control, however only Quian[10] and Witbeck[11] have published experimental work on closed underflow (water sealed) hydrocyclones. This work did not provide a model to design or size a desander, only experimental comparison for specific applications. Multiphase desanders models have not been addressed, which will be the subsequent work from this paper.

4 MULTIPHASE DESANDERS

4.1 History of Multiphase Desanders

A joint industry project (JIP) initiated in 1994 was set up to investigate the viability of using specially designed desanders for solids removal from multiphase production operations. The operators involved in the initial study were BP, Chevron, LASMO, Shell Expro, and Statoil[1].

The comprehensive development, from concept to commercial product, of the first wellhead desander was carried out in three stages. Internal testing at a cyclone vendor laboratory performed the initial phase of testing. This involved the investigation of air and water systems in controlled laboratory conditions focusing on the hydrodynamic relationship between pressure drop, flow rate, and gas void fraction (GVF) in a desander. Additionally, the sand removal efficiency at optimum flow parameters was tested to establish the design of a pilot unit. The second phase of work was JIP funded, and involved the construction and testing of a pilot plant at BP Wytch Farm onshore production facility. A third, parallel exercise was undertaken on a 5,000 psig (34,450 kPag) design pressure prototype wellhead desander to prove the mechanical viability of a commercial unit. Using successful laboratory and field data, the first commercial unit was manufactured and installed on the Shell Expro Brent Field, 18 months after first concept.

Since the installation of the first unit in 1995, at least 40 more units have been installed in the North Sea, Gulf of Mexico, Venezuela, Brazil, Saudi Arabia, Indonesia, and Canada. These units are split between wellhead and wellstream use, with the wellhead units in use as a service tool and the wellstream units in use for standard production. These units have ranged in size from 3-20 inch (75-500 mm) nominal diameter and from 150-10,000# rating (1033-68900 kPag). Vessel material of construction is carbon steel, 316 stainless steel, and standard/super duplex stainless steel. Internal wear components are typically made of boride hardened 410 stainless steel. Very high wear applications have added alumina (Al_2O_3) or silicon carbide (SiC) ceramic lining as tile or cast components.

4.2 Application and Use in Oil & Gas Industry

The first multiphase desanders units were installed upstream of the production choke and became termed “wellhead desanders”, as shown in Figure 3. As application base grew specific designs were made to operate downstream of the choke. These units were correspondingly termed “wellstream desanders”. Both units operate in multiphase flow and are of similar design. The main difference in each is due to mechanical design requirements. A wellhead desander may be designed for 5,000-15,000 psi API rating, while a wellstream desander is typically designed for 150#-600# ASME. Benefits of pre-choke installation include protection of the choke and all downstream process equipment, lower actual volume of fluids to be treated (smaller diameter desander), possible elimination of PSV as unit designed for full shut-in pressure. Well service companies have used wellhead desanders as a work-over tool. Benefits of post-choke installation include lower design pressure and potential to treat several wells through single unit. Primary wellstream desander installations are with oil companies to protect downstream process equipment (e.g. separators).

Multiphase desander technology can be a valuable tool for use by both oil producers as well as service companies. Generally the equipment is provided as permanent installation on operating systems, or as a portable skid for service company work. The initial design role was to remove solids from fracture flow back operation. Due to the flexible robust design, this scope has greatly increased to include many applications.

1. Removal of naturally produced formation sand from wells in which a gravel pack was never installed or has failed. A 30% increase in sand free production rate has been achieved in some applications.
2. Removal of sand flow back from coiled tubing fracture jobs, well bore flush out, or well acidizing.
3. Removal of solids from well fluids in underbalanced drilling operations.
4. Removal of solids from gas and condensate wellstream to prevent plugging of printed circuit heat exchanger technology used in gas well cooling applications.
5. Removal of sand from oil & gas well streams to protect sensitive downstream equipment, and avoid choke, manifold, and flow line erosion.
6. Monitoring and measurement of sand production rates (i.e. test unit).

Both the vessel and liner type desander configurations have been used in multiphase applications. Theoretically both configurations are applicable, however to date most installations have used the vessel style because it handles a higher solids loading, is less susceptible to plugging by large particles, has a smaller vessel diameter, and does not suffer from possible maldistribution of gas-liquid flow to cyclone internals. The liner style does have the advantage of finer separation size and modularized design that allows for simpler maintenance.

5 MECHANISTIC MODELS

5.1 Operating Principles

A multiphase desander operates on the same principles as a standard liquid only desander, except that it is designed to treat combined gas-liquid flow. The unit uses pressure energy from the wellstream fluid to achieve cyclonic separation of solids. The feed stream from the wellhead, a mixture of liquids (oil, drilling fluid, water, etc.), gas (natural, nitrogen, etc.), and solids (sand, scale, rust, etc.) enters the cyclone insert tangentially through the inlet. The change in flow direction forces the mixture to spin in a vortex pattern. This vortex flow is accelerated as the internal diameter is reduced over the length of the cone. Due to angular acceleration of the flow pattern, centrifugal forces are imparted on the solid particle forcing them toward the wall of the cone. The solids continue to spin in a radial vortex motion, down the length of the cone, to discharge through the apex creating the underflow stream. Due to the cone convergence, the multiphase fluid flow is reversed, and sent upward through the vortex finder to create the overflow stream. The solids that exit through the apex collect into an accumulation chamber, where they are periodically purged, while the overflow discharges continually. The presence of free gas in the feed stream has the beneficial effect of increasing inlet fluid velocity, decreasing the fluid mixture density and viscosity, and creating an annular liquid flow patch (gas core) that decreases the particle migration distance. These effects work together to increase the solids recovery efficiency.

The internal geometry of the cyclone insert is extremely important, and is driven by detailed knowledge of the fluid properties, multiphase flow regime, allowable pressure drop, and separation efficiency requirements. Conventions used in this paper for desander geometry are shown in Figure 4. Multiphase desanders have been applied to well fluids from 0-100% GVF, with the geometry customized for the process conditions, solids characteristics, and site space requirements.

5.2 Flow Regime

The methodology for determining pressure drop and separation efficiency of a multiphase desander has stemmed primarily from empirical scaling relationships based hydraulic and pneumatic cyclone models. To determine which base and scale model to apply, the inlet flow regime must first be determined. As a simplistic approach, low GVF applications are treated as hydraulic desanders with gas in the fluid (liquid dominant), and high GVF applications have been treated as pneumatic cyclones with a heavy wet gas inlet (gas dominant). The boundary line for which model to use is based on the determination of the inlet flow regime.

Desanders are normally operated in the vertical position, so the inlet line runs horizontally into the unit. Flow regime determination for two-phase flow in a horizontal line can be determined by several methods (Beggs-Brill[12], Gregory-Mandhane-Aziz[13], Taitel-Dukler[14], etc.). The first generation multiphase desander model uses the Gregory model because of the relative simplicity in plotting the flow regime map[13], as shown in Figure 5. Pipe geometry and fluid data determine the flow regime. Annular mist flow is deemed gas dominant and all other regimes (slug, dispersed, churn, etc.) are deemed liquid dominant. Liquid dominant flows are treated with the hydraulic cyclone model and gas dominant flows are treated with the pneumatic cyclone model.

5.3 Pressure drop

Pressure drop is the energy source for separation in any cyclone. It is also the only practical operating parameter that can be changed on-line to affect separation efficiency. The pressure drop is directly related to a cyclone flow rate, thus is controlled by the amount of fluid put through the unit. Increasing or decreasing the throughput, will have a directly proportional effect on the pressure drop.

A multiphase desander can operate over a wide pressure drop range providing an inherent turndown ratio. The recommended minimum operating pressure drop for a multiphase desander is 10 psi (69 kPa). Below this value, the fluid does not contain enough energy to form the proper vortex flow pattern. No theoretical maximum pressure drop exists, but 75-100 psi drop (517-689 kPa) is offered as a practical maximum. Above this value the wear rate continues to increase as velocity to the fourth power, while the added recovery is minimal. Liquid dominant flow regimes will generally produce a pressure drop in the 25-75 psi range (172-517 kPa), while gas dominant flow regimes will generally produce a pressure drop in the 15-40 psi range (103-276 kPa). Very dry gas flows may operate at 2-5 psi pressure drop (14-34 kPa), however this occurs in low-pressure gas only applications.

5.3.1 Liquid Dominant Flow

Hydrocyclones will have a specific pressure drop versus capacity relationship exhibited by the capacity power law. This law is shown in Equation 1 below to express the flow rate (*Q*) in terms of the pressure drop (*DP*).

$$Q = a(\Delta P)^{b} \qquad \text{Eq. 1}$$

The terms a and b are correlating factors to fit the mathematical relationship. For the desander geometry in which these correlations were developed (termed “standard geometry”), the power factor (*b*) in this relationship is found to average 0.5, which is the slope of the curve as plotted on an ln-ln graph. The equation then reduces to the simple relationship shown in Equation 2.

$$Q = k\sqrt{\Delta P} \qquad \text{Eq. 2}$$

The k term is called the “k-factor” and is specific for each hydrocyclone size and geometry. In effect it is similar to a listed C_v value for a valve. Cyclone diameter has the greatest directly proportional effect on k-factor, with inlet area, vortex finder diameter, and cyclone length exhibiting proportional lesser effects. The capacity relationship for a range of hydrocyclones is shown in Figure 6. These curves are determined by direct flow laboratory measurements.

The Hadfield-Rawlins[15] relationship is a modification of the capacity power law corrected for multiphase flow, and is shown in Equation 3.

$$\Delta P = \left(\frac{Q}{Gk}\right)^{2} \qquad \text{Eq. 3}$$

This is the same equation as previously presented, only factored for pressure drop. The k-factor is present, as in the standard desander relationship, and has the same function. A further “G-factor” (dimensionless) is present as an increase to the pressure drop due to the presence of gas. This increase in pressure drop is due to the actual fluid volume the free gas will occupy, that both increases the inlet velocity and increases the effective fluid volume present in the hydrocyclone. The G-factor was determined experimentally both in lab and subsequent field installations. The term was found to provide a distinct increase in pressure drop with increase in gas liquid ratio (v/v), as shown in Figure 7. This is a very simple approximation found valid for most field applications, although field data has been difficult to obtain. Further work will be undertaken to develop a mechanistic model from first principles to validate and extend the model.

This increase in pressure drop is measured for gas liquid ratios (v/v), up to approximately 20:1, above which it is assumed the flow regime is gas dominant (mist flow). Once the k and G factors are applied to the flow rate, the resultant pressure drop can be input into the separation size calculation.

5.3.2 Gas Dominant Flow

A pneumatic cyclone model is used for gas dominant flow in determination of pressure drop. The Stairmand relationship was selected both for its simplicity of calculation and applicability to the cyclone geometry tested[16]. The mist flow acts as a heavy gas and follows this curve closely. The formula for pressure drop calculation is shown in Equation 4.

$$\Delta P = \frac{N_H \rho_f Q^2}{2 K_a^{\,2} K_b^{\,2} D_c^{\,4}} \tag{Eq. 4}$$

$$K_a = \frac{a}{D_c} \tag{Eq. 5}$$

$$K_b = \frac{b}{D_c} \tag{Eq. 6}$$

The term N_H is a cyclone configuration constant, dependent upon the geometry. This value has been determined for standard geometry function. The Dukler mixing density[14] must be used for the fluid density (ρ_f), and the actual total liquid flow rate (gas plus liquid) is used as the capacity. The terms K_a and K_b relate the inlet height (a) and width (b) for a rectangular inlet design to the cyclone diameter (D_c). These terms can be calculated for a circular inlet using the hydraulic radius. This equation has been found to provide good correlation to liquid laden produced gas in field applications.

5.4 Separation Efficiency

Similar to pressure drop calculations, the algorithm for multiphase desander separation efficiency starts with determination of inlet flow regime. The gas or liquid dominant nature present at the multiphase desander inlet will determine the hydrodynamic and separation efficiency nature of the unit. A multiphase desander operating in the annular mist flow regime (gas dominant) will follow the recovery efficiency correlation of Leith-Licht for gas cyclones. Units operating in all other flow regimes (liquid dominant) follow the Lynch-Rao efficiency model for hydrocyclones. Once the inlet flow regime has been determined the corresponding correlation can be used to designate the proper multiphase desander configuration and model the separation efficiency and size.

5.4.1 Liquid Dominant Flow

The Lynch-Rao relationship modified for multiphase flow can be used for all liquid dominant flow regimes[17]. A thorough review of the basic relationship has been detailed in previous publications[2], and only the basics are presented here. The reduced recovery curve, base d_{50}, and actual d_{50} formulas are followed as the basis. The reduced recovery curve, also called graded efficiency curve, plots the recovery percentage for each particle size. It is called reduced because the flow split correction taken for a open underflow is removed to reduce the recovery to 0% for a particle of 0 microns. The base d_{50} is the particle size with a 50% chance of capture, based only on cyclone diameter. The actual d_{50} corrects the base d_{50} for cyclone geometry and fluid properties. The actual d_{50} is what the desander will exhibit when installed. Corrections for inlet concentration, inlet area, vortex finder diameter, body length, and cone angle remain the same, while the corrections for pressure drop, fluid viscosity, and fluid density are modified for multiphase fluids. The net result is to produce the actual d_{50}.

The pressure drop for multiphase flow is much higher than hydraulic flow for a given liquid rate as presented in the previous section. The correction to the base d_{50} can still be utilized, once the resultant (higher) pressure drop is determined.

Both the fluid density and viscosity are greatly changed by the presence of free gas. In a hydraulic desander, a solid particle must migrate through the carrier liquid, and is impeded by the liquid viscosity and density. The presence of gas has the benefit of changing the carrier fluid from a liquid to vapor-liquid mixture. The resultant mixture has a viscosity and density between the base constituents, as shown in the Dukler mixing relationships of Equations 7-9. First the liquid fraction (l) is determined from the actual gas (Q_L) and liquid (Q_G) flow rates. The resultant mixture density (r_M) and viscosity (m_M) are determined by rule of mixture relationships to the gas and liquid density (r_L, r_G) and viscosity (m_L, m_G) respectively.

$$l = \frac{Q_L}{Q_L + Q_G} \qquad \text{Eq. 7}$$

$$r_M = r_L l + r_G(1 - l) \qquad \text{Eq. 8}$$

$$m_M = m_L l + m_G(1 - l) \qquad \text{Eq. 9}$$

These equations must be calculated in-situ to account for the actual volume of gas at the process pressure and temperature. Once the mixture density and viscosity are known, the standard correction to base d_{50} can be used.

Using actual d_{50} for the specific hydrocyclone, the separation efficiency can be obtained. The actual d_{50} and the inlet feed particle size distribution are used with the recovery curve to calculate the percent recovery for each particle size. The shape of a recovery curve for a standard geometry desander is defined mathematically by the Lynch-Rao relationship shown in Equation 10, and illustrated in Figure 8. This equation can be used to calculate the recovery probability for each particle size in a range.

$$Y\left(\frac{d}{d_{50}}\right) = \frac{e^{a\frac{d}{d_{50}}} - 1}{e^{a\frac{d}{d_{50}}} + e^{a} - 2} \times 100 \qquad \text{Eq. 10}$$

In this equation the actual d_{50} is used, along with each particle size (d) and the sharpness slope (a). The sharpness slope varies with fluid and solid properties. The recovery (Y) for each particle is then summed up for the complete range to give a total recovery. The recovery percentage (E) is the relationship of the recovered amount-inlet solids content (f) minus overflow solids content (o)-to the inlet solids content, which is shown in more general terms for a hydrocyclone in Equation 11.

$$E = \frac{f - o}{f} x100 \qquad \text{Eq. 11}$$

The calculated cut size can further be used to generate the separation size. Using the Lynch-Rao relationship, with a of 4.0 (sand in water), the separation size (d_{98}) is equal to 1.97 times the cut size (d_{50}).

A relationship determined by Plitt can be used to calculate a for the Lynch-Rao equation[3]. Plitt uses Rosin-Rammler as an alternative to the Lynch-Rao equation, which defines a sharpness value m. The value for m can be calculated with Equation 12, and converted to α with Equation 13.

$$m = 2.96\exp(-1.58R_f)(\frac{D^2(L-l)}{Q})^{0.15} \qquad \text{Eq. 12}$$

$$a = 1.54m - 0.47 \qquad \text{Eq. 13}$$

Where R_f is the flow split to underflow (0 for desanders), L is the cyclone internal length, and l is the vortex finder length.

For general comparison, in a liquid dominant application a 4.0 inch (100 mm) multiphase desander will have a separation size of 25 microns, while a 20 inch (500 mm) desander will have a separation size of 100 microns. The practical limit for sand separation from a hydrocyclone is 10 microns.

5.4.2 Gas Dominant Flow

For applications involving annular mist flow, particularly gas wells, a different approach to separation efficiency is taken. A practical gas cyclone model developed by Leith-Licht is used for the cyclone design[18]. This model is based upon the fluid tangential velocity profile in Equation 14, where the product of the tangential velocity (v_q) and the radius (r) remains constant.

$$v_q r^m = cons\tan t \qquad \text{Eq. 14}$$

The exponent (m) was experimentally derived, and is given by Equation 15. It is shown to be a function of cyclone diameter (D_c) and temperature (T).

$$m = 1-(1-0.67D_c^{0.14})(\frac{T}{283})^{0.3} \qquad \text{Eq. 15}$$

The collection efficiency (η) per particle size (D_p) is further determined by Leith-Licht model given by Equation 16.

$$h(D_p) = 1-\exp(-yD_p^{M}) \qquad \text{Eq. 16}$$

In which Equations 17 and 18 give the main parameters y and M.

$$M = \frac{1}{(m+1)} \qquad \text{Eq. 17}$$

$$y = 2\left[\frac{KQr_p C_c (m+1)}{18mD_c^{\ 3}}\right]^{\frac{M}{2}} \qquad \text{Eq. 18}$$

The coefficients K and C_c are called the dimensionless geometric configuration parameter and the Cunningham correction factor respectively. Both values are specific to the hydrocyclone geometry, and are experimentally determined for a set geometry ratio. The particle density (r_p), gas viscosity (m), and cyclone diameter are the other main factors.

In the equations above, the fluid viscosity used must be corrected both for actual gas conditions, as well as the vapor-liquid mixture. This is easily taken into account using the Dukler mixture viscosity calculated at operating conditions. Cyclone geometric parameters such as inlet area, vortex finder, cylinder length, and cone angle are configured into the K and C_c values. Particle specific gravity is corrected to account for fluid mixture density. The flow rate instead of the pressure drop is used in the efficiency calculation, which is acceptable as they are directly proportional by a square power factor. The net result is similar to the actual d_{50} calculation for hydraulic desanders.

The resultant particle recovery curve is similar in style to the Lynch-Rao curve, but exhibits a slightly differing shape. Total solids recovery is calculated by summing each individual particle recovery fraction. The cut size and separation size values are determined from the above equations, calculated for the 50% and 98% sizes respectively.

For general comparison, in a gas dominant application a 4.0 inch (100 mm) multiphase desander will have a separation size of 15 microns, while a 20 inch (500 mm) desander will have a separation size of 50 microns. The practical limit for sand separation from a pneumatic cyclone is 10 microns.

5.5 Particle Trajectory

It is worthwhile to discuss the trajectory of solid particles in a multiphase desander. Since the utility of a multiphase desander is to remove sand particles from a mixed fluid stream, every effort in design and operation must be undertaken to separate and capture these particles. Transition from axial pipe flow to cyclone vortex flow is undertaken by the desander inlet transition. The transition both increases the fluid velocity (from 20-30 m/s to 75-100 m/s) and changes the flow direction (axial to centrifugal). Of key importance is to direct the randomly moving solids in the pipe to the cyclone wall as quick as possible. This is done with a tangential or volute inlet. Volute inlets, from 180-360º, provide a more efficient transition but are much more complicated to manufacture on pressure vessels. Typically tangential inlets are used, as the difference in efficiency is small compared to the lowered cost.

Particles that successfully translate to the cyclone wall are considered captured and follow the vortex flow along the inner wall of the cyclone cylinder and cone sections, as shown in Figure 9. As the radius decreases down the length of the cone, tangential velocity increases, which captures more and smaller particles. The boundary layer at the wall has a downward axial velocity that pushes particles towards the apex. If the boundary layer becomes overloaded with particles, some of the boundary layer flow may remix into the main vortex flow and leave with the overflow[3]. In an open underflow removal of boundary layer fluid is regulated the apex diameter, which controls the liquid split. On a desander an accumulating chamber seals the underflow reducing this flow rate to zero. For this reason the amount of solids a desander can handle in the inlet flow is limited to prevent overcrowding at the boundary layer and apex. Experimentally this value has been found to be 1 vol.%.

Once the particles are fully captured and report through the apex, they collect in the accumulating chamber, as illustrated in Figure 9. The solid particles have tangential, radial, and axial velocity components as they leave the apex, however because the accumulator is a static liquid filled chamber, the velocity is immediately arrested. The particles then settle by gravity through the liquid medium into the bottom of the accumulator. Most desanders are oriented vertically to allow solids to collect near the accumulator discharge orifice. Horizontal operation of a desander is possible (centrifugal separation forces negate gravity effects), however the apex must be designed to discharge solids at 90º to drop into the discharge orifice. The velocity arrest by static liquid coarsens the desander separation size compared to open underflow operation as small particles are unable to settle quickly and may be recaptured into the vortex flow. This elutriation effect of small particles does increase the sharpness of separation (increases a).

The effect of captured particles settling into the static accumulator is called "particle-fluid swapping". As a sand particle of given volume settles into the accumulator it displaces an equivalent volume liquid droplet upward into the desander, as illustrated in Figure 9. Gravity settling is a function of density therefore sand will settle in a water filled chamber however oil will not. A beneficial effect arising from this is that solids are washed while settling into the accumulator. To negate the coarsening effect of separation size by a closed chamber a net removal of liquid out of the chamber through an orifice other than the apex must be imposed. Liquid can be removed through the solids discharge orifice, however throttling of slurry in high-pressure applications leads to premature wear of valves. An alternative is to remove liquid from the top of the accumulation chamber. As long as the volume of liquid removed from the accumulator is greater than the volume of solids entering the chamber, no coarsening effect will occur. The simplest method is to provide a balance line from the top of the accumulator to the overflow line as shown in Figure 9. Controlling this flow with a spring balanced flow valve is an economic method of ensuring sufficient liquid removal without substantial support equipment. Connecting the balance line to the overflow is a convenient location as it keeps all liquids within the desander package, and it minimizes the pressure drop on the flow valve (it will be equivalent to the inlet-overflow pressure drop). This effect has been exhibited in field applications but no comprehensive study has been undertaken to quantify the liquid removal rate versus increase in separation efficiency.

6 CONCLUSIONS AND FUTURE WORK

The purpose of this paper is to provide an overview of the history, application, and function of multiphase desanders. A wide variety of material is presented to form the basis of a multiphase desander model using hydraulic and pneumatic cyclone models. A comprehensive understanding of the hydrodynamics and separation theory has been leapfrogged by the industry with little negative effect on equipment deployment and use. The simplicity of cyclone operation has enabled these theoretical gaps to be covered by adjustment in operation, as most units installed in the field have provided excellent separation characteristics. Variation in unit life has been exhibited, which is mainly attributed to improper material selection or misapplication of the technology. Overall the multiphase desander has proven to be a robust addition to the process engineer tool kit in solving solids separation problems in oil and gas production operations.

Work has recently begun to produce a comprehensive hydrodynamic model for determination of pressure drop and separation efficiency at the various flow regimes. This work will be undertaken with a transparent multiphase cyclone test loop using air-water-sand. Further work includes visualization and modeling of desander-accumulator interaction (fluid-particle swapping), solids settling and stacking mechanisms in accumulators, fluid partitioning in liner type vessels, desander orientation effect on separation, and pressure recovery with tangential overflow.

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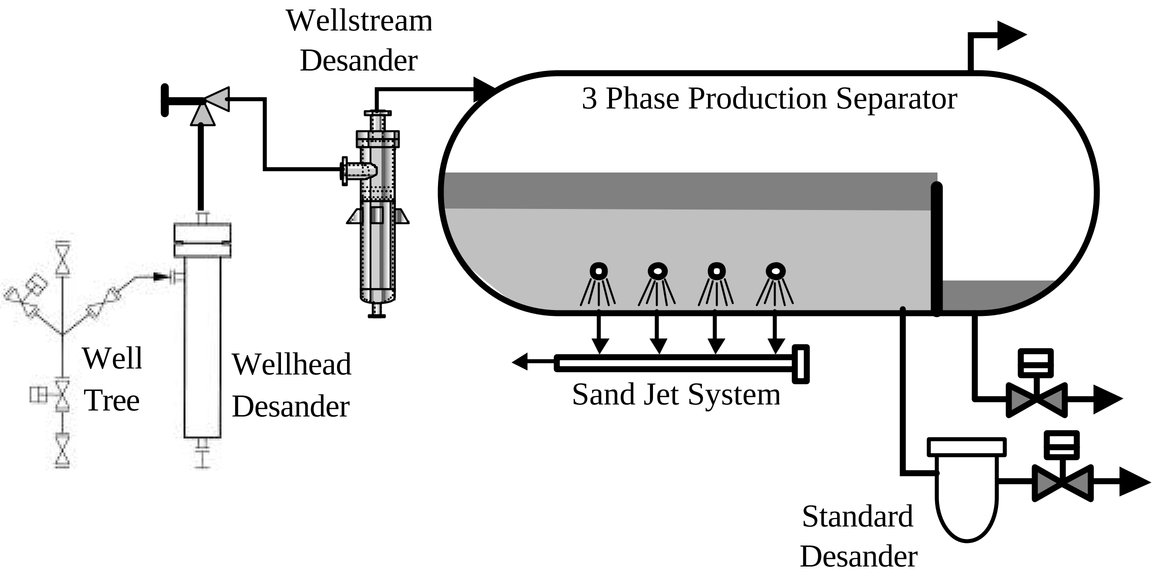

Figure 1: Solids removal options in typical production scenario.

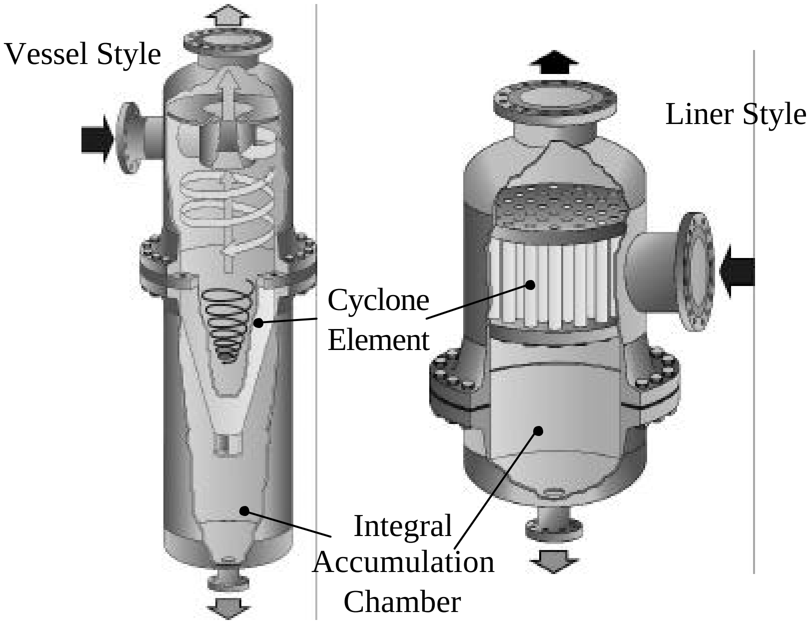

Figure 2: Desander geometry and types - vessel style (left) and liner style (right).

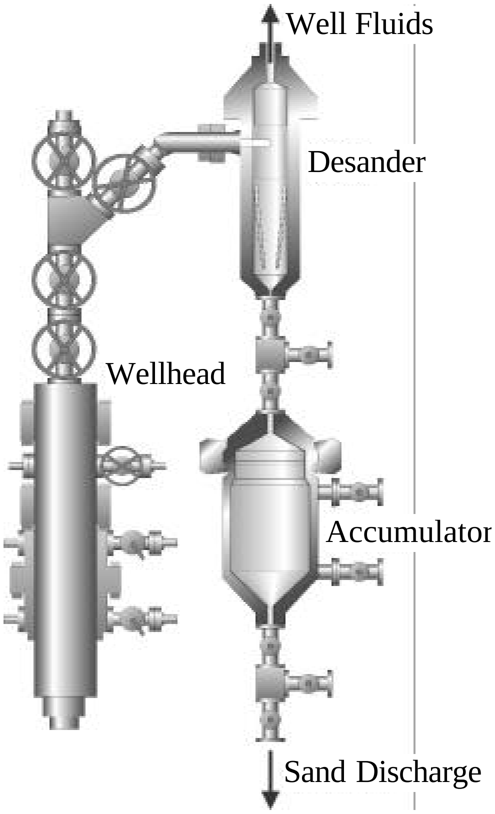

Figure 3: Application layout of wellhead desander.

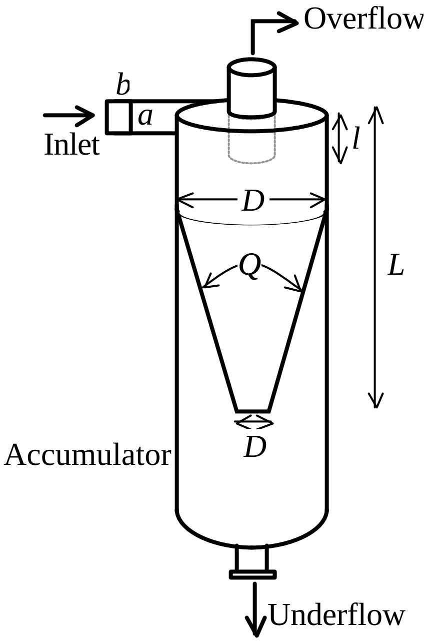

Figure 4: Desander geometry conventions use in mechanistic models.

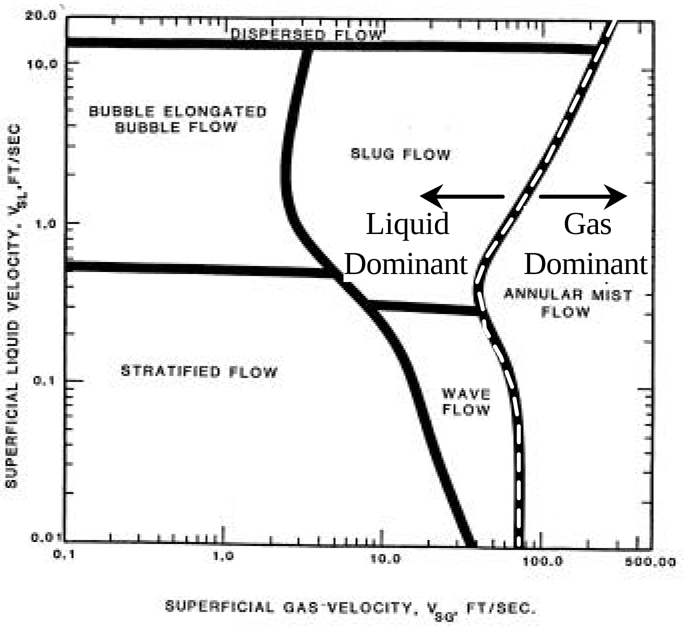

Figure 5: Gregory-Mandhane-Aziz flow regime map for horizontal pipes.

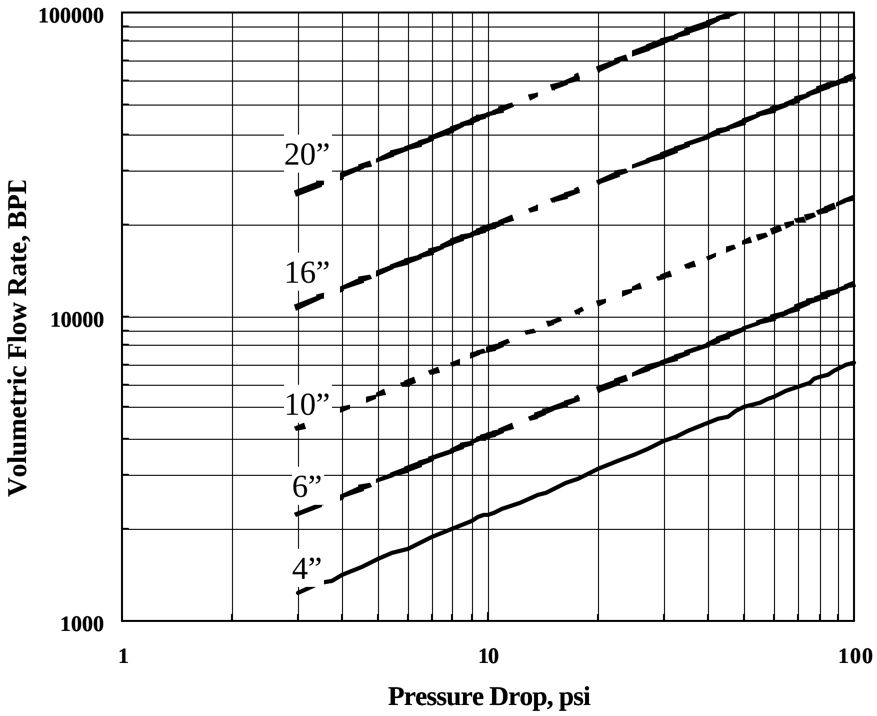

Figure 6: Hydraulic (water) capacity relationship for various desander sizes.

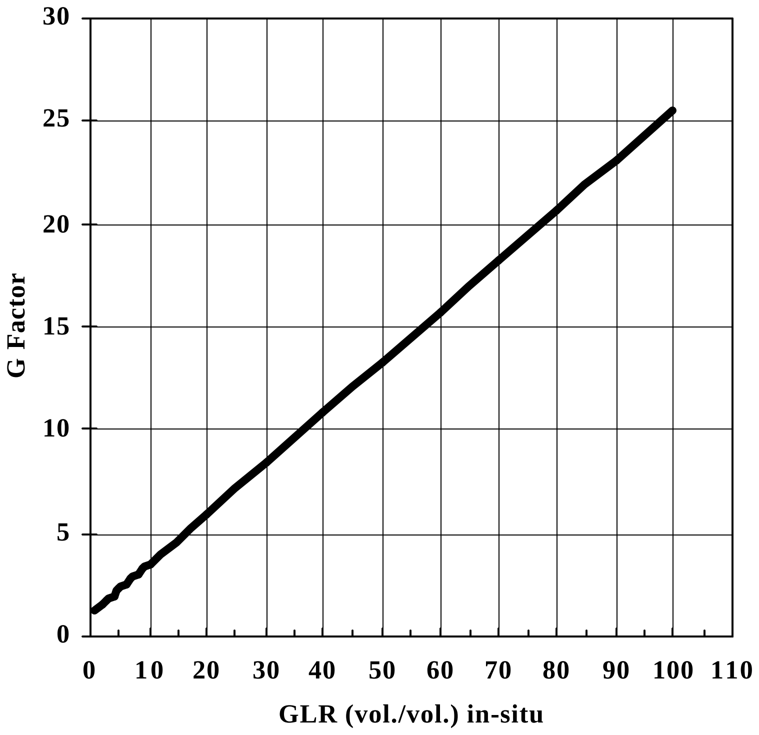

Figure 7: Hadfield-Rawlins relationship for gas effect on pressure drop (G-factor).

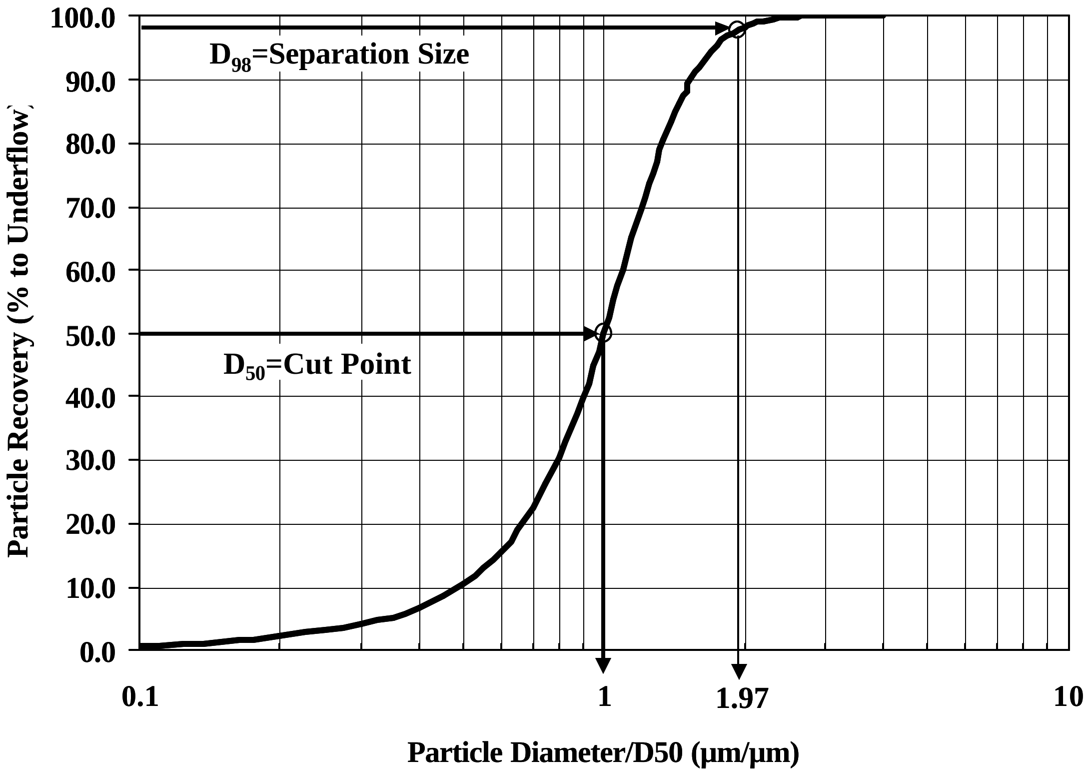

Figure 8: Reduced recovery curve shown as Lynch-Rao relationship.

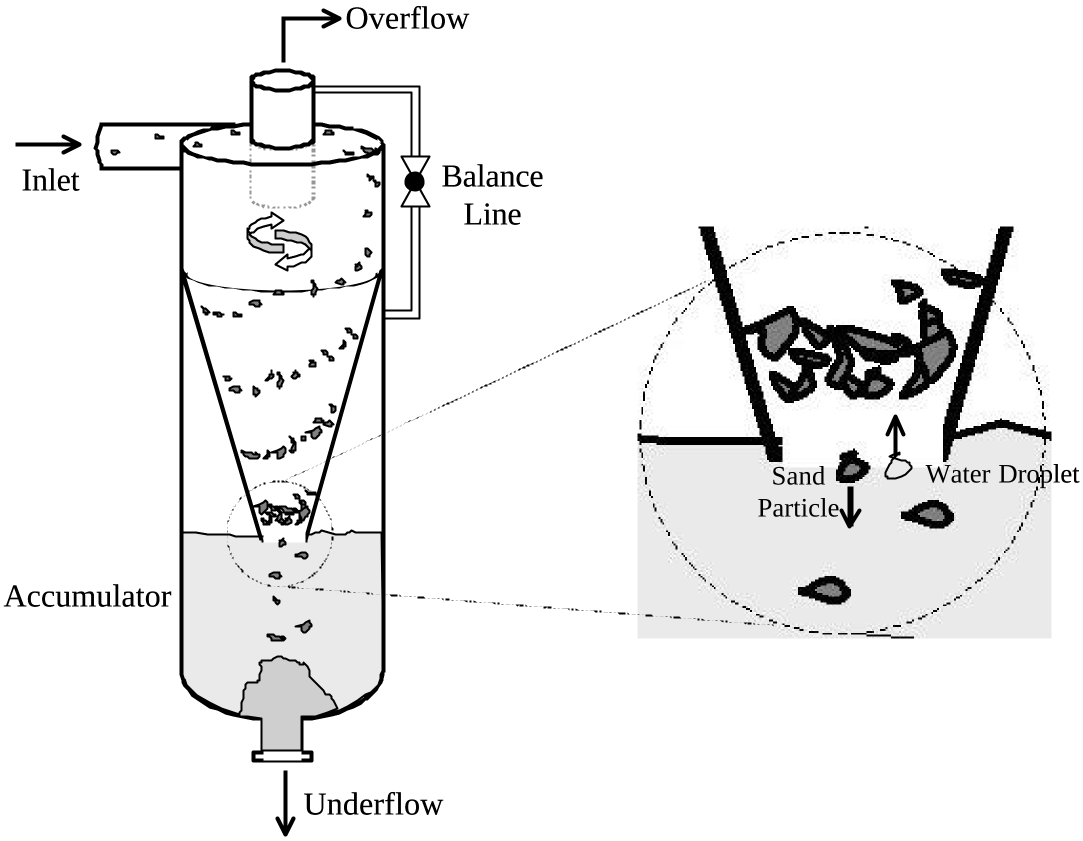

Figure 9: Particles trajectory in desander (vortex flow and "particle-fluid swapping").