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Three-Phase Separation Technology Study for Use Downhole in an Oil-Bearing Medium

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ABSTRACT

This research focuses on the three-phase separation of oil–water–solids that may be encountered in oil-bearing media. Developing a process to perform this three-phase separation downhole in the oil-bearing media leads to significant financial advantages. This research involves the use of a hydrocyclone unit to perform the separation. The unit is then used in conjunction with a centrifugal separator to further purify the streams. A separation efficiency is developed to predict the maximum separation possible for each of the phases present in the system. At specific operating conditions, a good separation is demonstrated for removing solids, as well as the separation of the liquids into two separate streams. The removal of the solids, with

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the remaining liquids exiting together in a separate stream, is also accomplished using the hydrocyclone unit. The research spans a range of feed compositions to simulate the possible process fluids that may be generated in an oil production process. This research indicates that the hydrocyclone can operate very efficiently in the three-phase system of a downhole oil-bearing media. Performance of the hydrocyclone can also be readily predicted for the solid and liquid separations.

Key Words: Downhole; Oil wells; Oil production; Downhole separations; DOWS.

INTRODUCTION

This research activity focuses on the extent of separation of the three major components encountered in oil-field applications, solids, oil, and water, by a small-scale hydrocyclone. This activity is a part of the development of advanced oil–water separator equipment for downhole oil well applications. A schematic of the advanced oil/water separation system being developed at the Oak Ridge National Laboratory (ORNL) is shown in Fig. 1. The oil–water separation in this program utilizes an ORNL centrifugal separator[1]; the current separator design is thought to have a low tolerance to solids.[2] This need to control the solids content in the feed to the oil–water separator is the primary motivation for the current study. Extensive research has been performed on hydrocyclones for solid–liquid separation, and this technology is used extensively in the oil industry. This research investigates the separation of all components, solids–water–oil, over a broad range of oil to water ratios. The range of oil to water ratios used in these tests simulates produced fluids encountered over the life of an oil well. The application of the results of this study is for the design and operations simulation of a solids separation unit, to function upstream of an oil–water separation unit. Both of these units are expected to function in an integrated process, with a primary purpose to separate oil and water in the oil-bearing media of the oil field, commonly referred to as downhole separation.

There are several methods of bringing produced fluids to the surface. In general, the use of the ORNL oil–water separator appears to be compatible with only continuous flow of produced fluids, such as from centrifugal pumps. Current commercial hydrocyclone-based downhole oil–water separation (DOWS) systems are usually operated in wells with water-to-oil ratios of 5 to 100 and usually result in a production stream

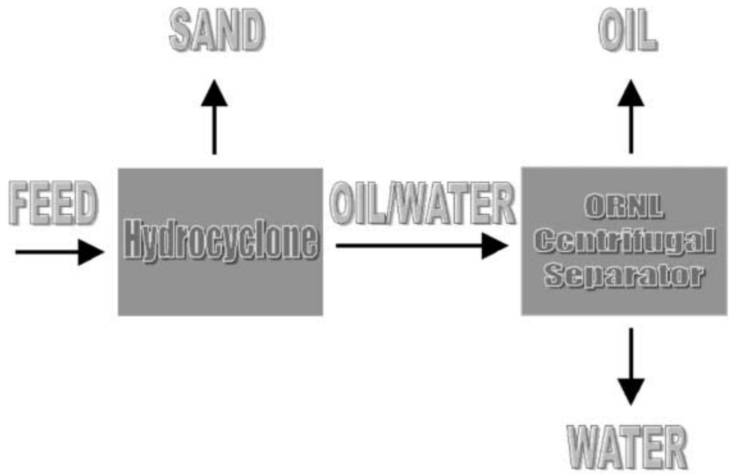

Figure 1. Advanced oil water separation system being developed at the Oak Ridge National Laboratory (ORNL).

that has a 1 to 2 water-to-oil ratio.[3] Currently, downhole separation systems are only economically feasible for on-shore applications where high-transportation and treating costs for water are considerations or where high water production limits oil production. The currently available downhole separation systems have not shown the reliability needed to incorporate them extensively offshore.[3]

The hydrocyclone was selected for use because it is a well-developed solid–liquid separation device and has acceptance in other downhole applications. The volume ratio of overflow (flow out of the top of the hydrocyclone) to underflow (flow out of the bottom of the hydrocyclone) streams is called the "split" and is usually adjusted by restriction on the underflow stream. See Fig. 2 for a schematic of a hydrocyclone. The split does not have to be the same as the feed ratio of the substances to be separated.[4] The feed ratio, as used in this report, is defined as the volume of oil per volume of water in the feed stream.

BACKGROUND

Although the primary purpose of our research is solids removal from produced fluids, the extent that oil and water are separated is of importance in

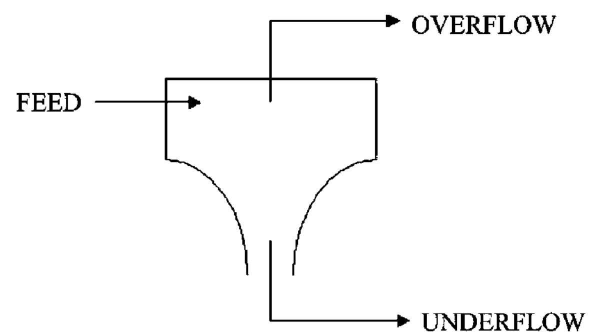

Figure 2. Figure for a material balance around the hydrocyclone.

future use of this technology. The main types of hydrocyclones discussed in this paper are liquid–solid hydrocyclones and liquid–liquid hydrocyclones. A liquid–liquid hydrocyclone is designed to separate two immiscible liquids. A solid–liquid hydrocyclone is designed to separate solid particles from the liquid stream. The liquid–liquid units have a typical length-to-diameter ratio of 20 to 40, while solid–liquid units have a typical length-to-diameter ratio of 5 to 8.[3] The pressure drop required for both solid–liquid and liquid–liquid separation by hydrocyclones generally ranges from 1 to 5 bar.[5] The pressure drop is measured from the inlet to the hydrocyclone to either of the outputs from the hydrocyclone.

Solid–liquid hydrocyclones can typically produce forces up to about 1000 g's or more and have residence times of seconds or less.[6] Feed concentration, liquid viscosity, particle size, and hydrocyclone geometry are some factors that affect hydrocyclone performance.[7] Particles that are separated by hydrocyclones are generally in the range of 40 to 400 μm but can range from 5 to 1000 μm in special applications.[3] A typical density of these particles is 1.5 to 2.0 g/mL. The forces of interest in a hydrocyclone are centrifugal forces and drag forces. If the centrifugal force is greater than the drag force, the particle moves outward toward the wall of the hydrocyclone. If the centrifugal force is less than the drag force, the particle moves toward the center of the hydrocyclone.[8] The result of this centrifugal field is that the heavy phase (particles) accumulates at the wall of hydrocyclone during typical operation. The substances at the wall of the hydrocyclone can then be removed through the underflow steam exiting the bottom of the separator.[9]

Liquid–liquid hydrocyclones separate two immiscible liquids. One example of a liquid–liquid hydrocyclone has a 30-mm diameter, 16-mm apex (underflow exit), L/D ratio (length/diameter ratio) ~15, and two inlet ports.[10] Another liquid–liquid hydrocyclone has the dimensions 35-mm diameter and L/D ~ 38.[11] The L/D ratio of the liquid–liquid hydrocyclones is much larger than the comparable solid–liquid hydrocyclones. This increased L/D allows for a longer residence time to aid in the liquid–liquid separation. As the fluids go through the unit, the lighter fluid moves toward the center of the hydrocyclone. At a point in the apparatus, the velocity in the vertical direction reverses and forms a flow (spiral path) back up. The heavier phase is at the wall of the separation unit and exits out of the bottom of the hydrocyclone. The flow in the center of the hydrocyclone exits in the overflow out the top.[9]

THEORY

An equation is provided for estimating the cutsize of a hydrocyclone, as well as for predicting the maximum theoretical separation efficiency for liquid separation and solid separation. Additional equations to determine the cutsize can be found in a master's thesis by Perkins.[3]

Cutsize

One measure of hydrocyclone efficiency is the cutsize (d_{50}) produced in the underflow stream; the d_{50} is the diameter of a particle having the same possibility of going to the overflow as going to the underflow.[12] Bradley[8] developed the following equation to estimate d_{50}:

$$d_{50} = \frac{3(0.38)^n D_i^2}{\alpha} \left[\frac{\tan(\Theta/2)\mu(1 - R_f)}{D_c Q \Delta\rho} \right]^{0.5} \tag{1}$$

where

d_{50}	cutsize	(m)
D_i	diameter of the inlet of the hydrocyclone	(m)
R_f	volume ratio of feed to underflow	(−)
D_c	hydrocyclone diameter	(m)
Q	flow rate	(m^3/s)

n	hydrocyclone specific parameter (normally assumed ~ 0.6)	(−)
α	ratio of wall velocity to inlet velocity	(−)
μ	viscosity of the liquid	(kg/m-s)
$\Delta\rho$	density difference of components	(kg/m^3)
Θ	included angle at cone apex	(rads)

In general, d_{50} increases with increasing viscosity and hydrocyclone diameter. Napier-Munn found that increased viscosity leads to a poorer separation quality, that is a higher d_{50} value.[13] The feed flow rate and density difference of the two phases is inversely proportional to d_{50} in the equation given above. Empirical tests are generally better for achieving a reliable value for a given separation problem, but the previous equation provides a good approximation.[6]

Efficiencies

The equations used to predict the liquid and solid separation efficiencies are derived as follows. Note that the liquid-phase efficiencies are calculated on a solid-free basis. The liquid separation efficiency is the fraction of the light component fed to the unit that reports to the hypothetical pure light phase component in the overflow. The solid separation efficiency is the fraction of the total solids fed to the unit that reports to the underflow.

Liquid-Phase Separation Efficiency

To develop an efficiency for the liquid separation, consider the overflow stream. This is the stream that is rich in the lighter phase (oil). Assume that the overflow exiting the hydrocyclone consists of a fraction that is of the same composition as the feed stream and another fraction of pure light phase. Define the mass fraction of the overflow that is pure as ϕ. The liquid phase separation efficiency, E_{LP}, of the separator may then be defined as:

$$E_{LP} = \frac{\text{hypothetical pure liquid light phase in the overflow}}{\text{light phase in feed liquid}} = \frac{Q_O \phi}{Q_F y_F} \quad (2)$$

where

E_{LP}	liquid-phase separation efficiency based on the light phase	(−)
Q_O	flow rate of the overflow stream	(g/s)

Q_F	flow rate of the feed stream	(g/s)
y_F	fraction of the feed consisting of the light phase	(−)
$1-\phi$	fraction of the overflow stream that is at the feed composition	(−)

A mass balance for the light phase in the overflow may be written as

$$Q_O y_O = Q_O(1-\phi)y_F + \phi Q_O \tag{3}$$

where

Q_O	flow rate of the overflow stream	(g/s)
y_O	fraction of the overflow consisting of the light phase	(−)
y_F	fraction of the feed consisting of the light phase	(−)
ϕ	fraction of the overflow stream that is at the feed composition	(−)

which when solved for ϕ yields

$$\phi = \frac{y_O - y_F}{1 - y_F} \tag{4}$$

When combined with the efficiency expression this, in turn, yields

$$E_{LP} = \frac{Q_O(y_O - y_F)}{Q_F y_F(1 - y_F)} \tag{5}$$

In deriving this efficiency expression, we compared overflow composition with the feed composition, but we could just as well have expressed the efficiency in terms of the heavy phase. Both of these expressions are numerically the same and refer to the liquid-phase separation efficiency of the hydrocyclone. By defining the efficiency in this manner, we are acknowledging that 100% efficiency can only be obtained if both the exiting streams are only one pure phase.

$$E_{HP} = \frac{Q_U(y_F - y_U)}{Q_F y_F(1 - y_F)} \tag{6}$$

where

E_{HP}	liquid-phase separation efficiency based on the heavy phase	(−)
Q_U	flow rate of the underflow stream	(g/s)
Q_F	flow rate of the feed stream	(g/s)
y_F	fraction of the feed consisting of the light phase	(−)
y_U	fraction of the underflow consisting of the light phase	(−)

Given the overflow/underflow ratio and the feed ratio of the liquids, the theoretical maximum liquid separation efficiency was calculated from eq. (5).

Solids

From a material balance on the solid phase in the above system, we obtain the following equation:

$$Q_F Y_F = Q_O Y_O + Q_U Y_U \tag{7}$$

where

Q_F	mass flow rate of feed	(g/s)
Q_O	mass flow rate of overflow	(g/s)
Q_U	mass flow rate of underflow	(g/s)
Y_F	mass ratio of solids to liquids in the feed	(−)
Y_O	mass ratio of solids to liquids in the overflow	(−)
Y_U	mass ratio of solids to liquids in the underflow	(−)

The solids separation efficiency (E_S) is given by the mass of solids in the underflow divided by the mass of solids in the feed stream:

$$E_S = \frac{Q_U Y_U}{Q_F Y_F} \tag{8}$$

where E_S is the solids separation efficiency.

OPERATION

Equipment

A schematic of the experimental setup is illustrated in Fig. 3. The equipment used to perform this research includes two 55-gallon stainless steel drums for feed and recovery tanks, a 10-mm inside diameter stainless steel hydrocyclone (Dorr-Oliver Inc. of Milford, CT—model no. Doxie A), two 0.5-hp mixers (Leeson Electric Corp. of Graftom, WI—model no. C6C17FB1E), a variable pressure, 2-hp, feed pump (Hays Pumps of Redding, CA—model no. Quantum VS 7A200), a one-third hp transfer pump (Ebara International Corp. of Rock Hill, SC—model no. 327707U 6.3S), a pressure gage on the feed line (0–150 psig made by 3D Instruments Inc. of Huntington Beach, CA—model no. DD504-24), two flow meters (Kent Meters Inc. of Ocala, FL—model no. KMJ Bronze), one Whitey needle valve (Swaglok Corp. of Solou, OH—model no. SS-18RS8), one Whitey semi-needle valve (Swaglok Corp. of Solou, OH—model no. SS1RS8), and four on/off valves (NUPRO Co. of Willoughby, OH—model no. SS8P6T). The transfer lines were one-half-inch stainless steel tubing.

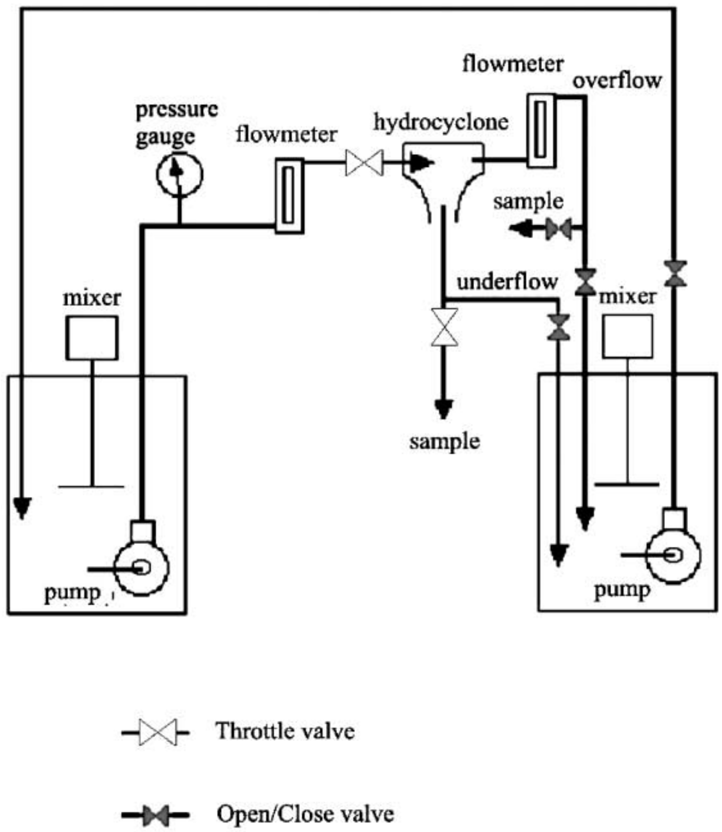

Figure 3. Experimental design of research apparatus.

The most important piece of equipment, however, was the 10-mm hydrocyclone (inside diameter). The hydrocyclone used was stainless steel and designed to remove solids from the liquid phase. This 10-millimeter (inside diameter) hydrocyclone has a natural volume split of 3:2 (overflow-to-underflow). A control valve can be used to throttle the underflow and change the split; Dorr Oliver Inc. recommends not exceeding a split of 10:1.[14] The hydrocyclone was mounted upright to aid in cleaning and draining of the unit. This unit will handle about 0.9 gallons per minute at 40 to 60 psig. It was recommended by the manufacturer that the pressure differential across the hydrocyclone not be less than 40 psig. Tests were performed at different oil to water ratios and different feed pressures with at least three different splits for each set of operating conditions. Partially closing the underflow valve decreased the rate of the underflow and changed the split. This research used a needle valve for split control, but rubber tubing and pinch clips were also used. The procedure used in this research was to begin the experiment with the underflow valve fully open and close, as desired.

Materials

Kendall 10-W nondetergent motor oil was used to give an organic layer as close to crude oil as possible but with known characteristics. The density of the oil was measured to be 0.869 g/mL and the viscosity was given as 4.3 cP at 100°C. The sand used to simulate solid particles in the produced fluids was white quartz sand and was supplied by Aldrich Chemical Inc. of Milwaukee, WI. Substitute seawater was prepared according to ASTM D1141-90 standard. The materials for the substitute seawater included potassium chloride (KCl), sodium bicarbonate ($NaHCO_3$), sodium chloride (NaCl), and sodium sulfate (Na_2SO_4), all supplied by Fisher Chemical Co. of Fair Lawn, NJ. Other materials needed were potassium bromide (KBr), boric acid (H_3BO_3), and sodium bromide (NaBr), which were supplied by Aldrich Chemical Inc. of Milwaukee, WI. Sodium hydroxide (0.1-N NaOH) was also needed and was supplied by Mallinckrodt Chemical Inc. of Paris, Kentucky.

Procedures

The feed mixture for the first set of experiments was selected and prepared by adding the appropriate amounts of oil and substitute seawater to the feed drum. Three percent sand by weight was added to the drum. Both mixers were placed in the first drum to ensure homogeneity of the feed. The variable speed pump was set to a feed pressure of 40 psig, and the valves from the top and bottom of the hydrocyclone set fully open. The feed mixture was placed in the feed drum and the mixers turned on. The mixers were left running for 5 minutes to ensure that good mixing of the feed occurred. The feed pump was then turned on and the system allowed to reach steady state at the specified pressure. The feed pressure determined the flow rate through the hydrocyclone according to manufacturer specifications. It should be noted that the feed was stirred and pumped through a centrifugal pump to the hydrocyclone, which may cause emulsification to some degree.

Once steady state was reached in the system, the samples were collected from the overflow and underflow streams from the hydrocyclone. The samples were collected simultaneously in 600-mL beakers. The dry beakers were weighed and recorded prior to taking the samples. The feed concentration was determined by the combination of the two flows. The samples were collected for 5 seconds, which was timed on a stopwatch. Three samples of each flow were collected for consistency. Prior to covering the beakers with parafilm, the beakers were weighed to get a total sample weight. The beakers were covered with parafilm to avoid evaporation. The samples were allowed to sit undisturbed overnight to assure a good separation of the oil and water components of the samples.

Additional beakers were weighed for collection of the oil when it was removed from the samples. In order to analyze the samples, the equipment needed included a 100-mL pipette, a pipette bulb, filter paper, a fritted disk filter, a filtration flask, and hexane. After the samples had sit undisturbed overnight, they were analyzed by first removing the oil. To the extent possible, the oil was removed from the beaker by a pipette. The oil was removed carefully so as not to remove any water or solids. Once the physical oil removal was complete, 30 milliliters of hexane was added to the beaker, and the beaker lightly agitated to dissolve the remaining oil. The hexane was removed and added to the previously removed oil in the same manner. This procedure allowed water and solids to remain in the sample beaker. The oil removed was placed in a hot water bath for 30 to 60 minutes, until the hexane had evaporated from the oil. Another alternative was to let the sample sit open overnight and allow the hexane to evaporate at room temperature in a fume hood. When the smell of hexane in the sample was no longer present, the evaporation was considered complete. Once the smell of hexane was gone from the beaker, the oil weight was measured. After adding an additional 10 mL of hexane to the sample, the water and solids were then vacuum filtered through the fritted disk. The sample was filtered until only hexane and solids were visible in the filter. The solids were allowed to remain in the hexane for about 5 minutes to remove any trace amounts of oil that may be trapped in the solids. The hexane was filtered from of the solids, and the solids washed into a beaker using distilled water. The fretted disk funnel was washed between samples to prevent contamination. The solids were recovered using previously weighed filter paper in the fritted disk funnel. The filter paper and solids were dried overnight and weighed to obtain the mass of the solids in the sample. By subtracting the mass of the oil and solids from the total mass of the sample, the mass of the water was determined.

RESULTS

The solid and liquid separation efficiencies are shown first as a function of overflow/underflow ratio. This gives an indication of separation performance of the hydrocyclone unit for the immiscible liquids in the feed stream. The data are then presented in the slightly more usable format of fractional recovery. Here, the fraction of each component separated to the appropriate stream was plotted as a function of overflow/underflow ratio. The results are then summarized in some concluding remarks. For each set of conditions studied in this research, three data points were taken to obtain the reproducibility of the results.

Efficiency

A plot of the particle-size distribution of the sand, as determined by the use of sieves, is presented in Fig. 4. The density of the sand was measured to be 1.539 g/mL. Equation (1) was used to predict the expected cutsize for our tests. The particle sizes of the solids used are higher than the predicted cutsize. This led to the expectation that nearly 100% of the solids would separate out in the hydrocyclone.

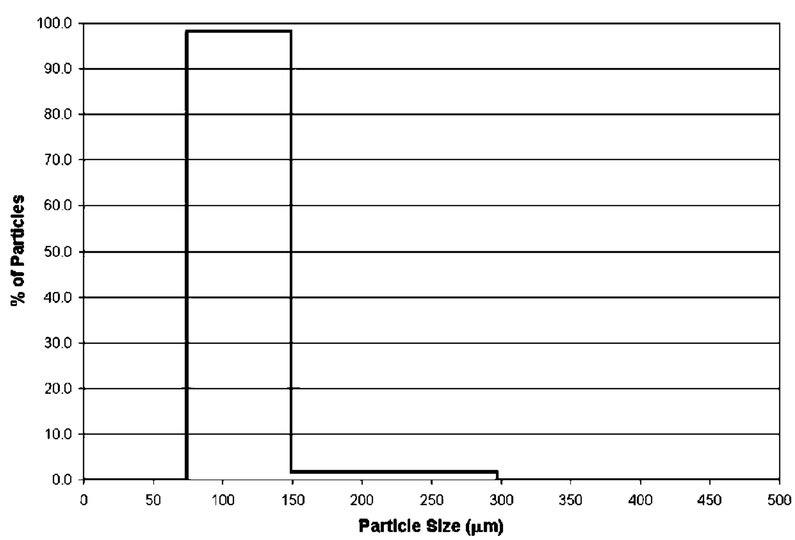

Figure 4. Particle size distribution for the solids used.

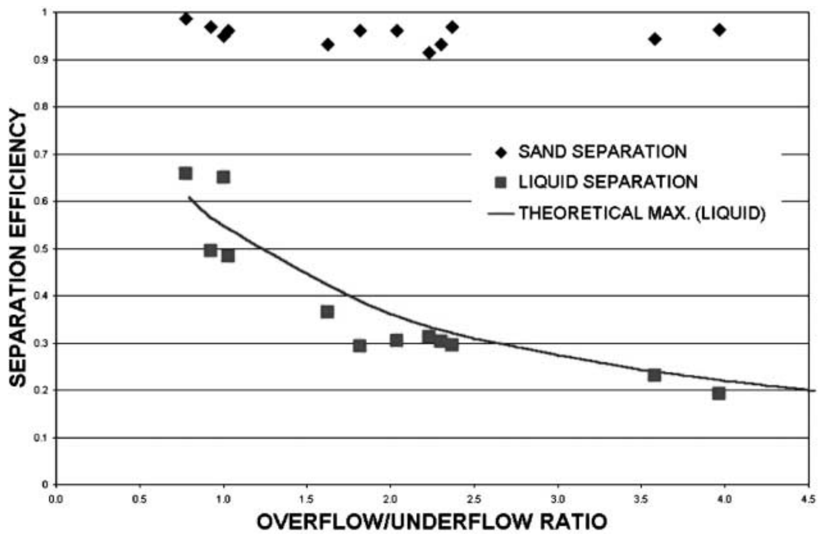

Figure 5. Comparison of separation efficiency with theoretical maximum predicted efficiencies in terms of overflow/underflow ratios (1/9 oil-to-water volume ratio) and a theoretical solids separation efficiency of 1.

Shown in Fig. 5 are the experimental solids separation efficiency and the experimental and theoretical maximum liquid separation efficiencies as a function of overflow/underflow ratio. The feed stream for this data consisted of a 1/9 oil-to-water feed ratio (volumetric). The solids separation efficiency showed no decrease with increasing overflow/underflow ratio but was consistently greater than 90%. The experimental liquid separation efficiency showed a decrease from the initial value of about 70% to about 20%, as the overflow/underflow ratio increased. The experimental liquid separation efficiency was close to the theoretical maximum separation efficiency [as predicted by Eq. (5)] for this feed. The solid separation efficiencies had an average standard deviation of 0.0189, and the liquid separation efficiencies had an average standard deviation of 0.0615.

Shown in Fig. 6 are the experimental solids separation efficiency and the experimental and theoretical maximum liquid separation efficiencies as a function of overflow/underflow ratio. The feed stream for this data consisted of a 1/1 oil-to-water feed ratio. The solids separation efficiency showed a possible decrease with increasing overflow/underflow ratio but is

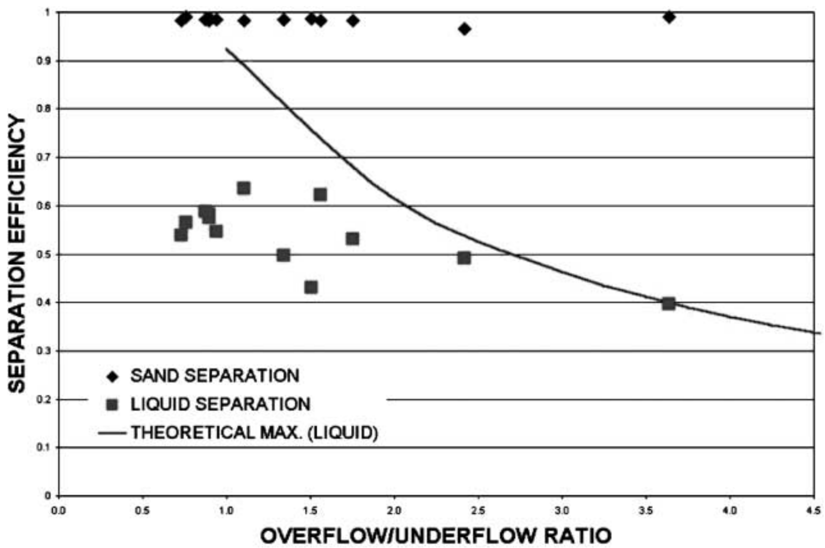

Figure 6. Comparison of separation efficiency with theoretical maximum predicted efficiencies in terms of overflow/underflow ratios (1/1 oil-to-water volume ratio) and a theoretical solids separation efficiency of 1.

consistently greater than 95%. The initial liquid separation efficiency is less than the theoretical maximum liquid efficiency [as predicted by Eq. (5)]; but as the overflow/underflow ratio increased, the measured liquid separation efficiency approached the theoretical maximum liquid efficiency. It should be noted that with a 1/1 mass ratio of oil to water fed to the unit, the maximum liquid separation efficiency should be unity at an overflow/underflow ratio of 1. The overflow/underflow ratio, as used in this report, is on a volume basis, except for the previous example. The volume basis chosen in this research accounts for the fact that the maximum liquid separation efficiency was slightly less than one in Fig. 6. The solid separation efficiencies had an average standard deviation of 0.0042, and the liquid separation efficiencies had an average standard deviation of 0.0432.

Shown in Fig. 7 are the experimental solids separation efficiency and the experimental and theoretical maximum liquid separation efficiencies as a function of overflow/underflow ratio. The feed stream for this data consisted of a 9/1 oil-to-water feed ratio. While the solids separation efficiency showed a slight decrease with increasing overflow/underflow ratio, the decrease was not determined to be statistically significant. The solids separation efficiency was

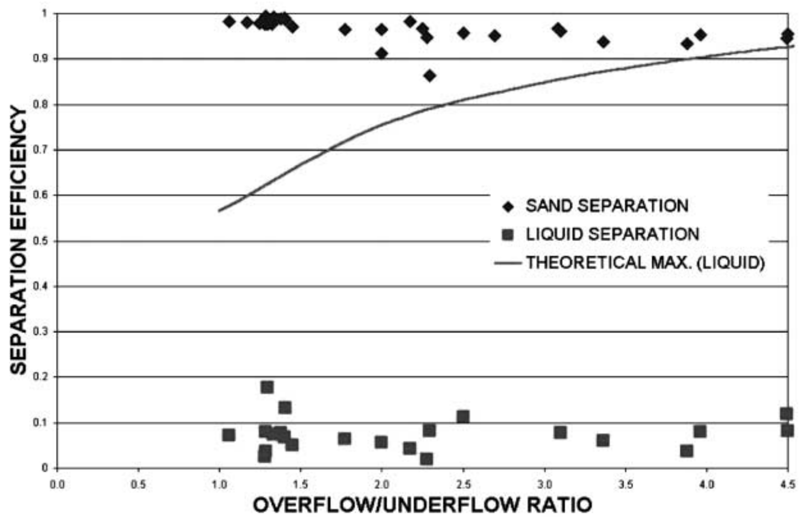

Figure 7. Comparison of separation efficiency with theoretical maximum predicted efficiencies in terms of overflow/underflow ratios (9/1 oil-to-water volume ratio) and a theoretical solids separation efficiency of 1.

consistently greater than 90%. The experimental liquid separation efficiency showed no increase from the initial value of about 10%, as the overflow/underflow ratio increased. The experimental liquid separation efficiency was not very close to the theoretical maximum separation efficiency [as predicted by Eq. (5)] for this feed. The solid separation efficiencies had an average standard deviation of 0.0166, and the liquid separation efficiencies had an average standard deviation of 0.0476.

Here are some general comments and conclusions on Figs. 5 through 7 just discussed. One note is that the liquid separation efficiency was considerably less than the theoretical maximum liquid efficiency for feed streams that were $>50\%$ oil; this is consistent with the results of Day, who reports that feeds that are mainly oil are harder to separate and result in a drastic drop in the liquid separation efficiency.[6] The experiments with feeds of predominantly oil had more water carryover into the oil stream (overflow) than did the experiments with feeds of predominantly water; these observations agree with those reported.[6] The theoretical maximum liquid efficiency could be used to predict the liquid separation efficiency in water-rich systems, but not in oil-rich systems.

Fractional Recovery

Next, we considered the separation data in a slightly different format. Instead of assessing the overall efficiency for the separation of the hydrocyclone, consider the fractional recovery in the respective streams. The goal of this research was to provide as much of the oil and water in the overflow of the hydrocyclone as possible, while minimizing the amount of solids. With this in mind, the data were further analyzed. The solids recovery is the fraction of solids entering the system that was recovered in the underflow. The oil recovery is the fraction of oil entering the system that was recovered in the overflow, while the water recovery is the fraction of water entering the system that was recovered the underflow. This method of plotting the data was used because some water must exit in the underflow to carry the solids.

Shown in Fig. 8 is the fraction of the solids, oil, and water recovered in the appropriate streams, as a function of the overflow/underflow ratio. These data were for a feed ratio of 1/9 oil-to-water. The fraction of solids fed into the system that were removed in the underflow was consistently above 90%. With respect to the liquids, about 60% of the water went into the underflow at low overflow/underflow ratios. At high

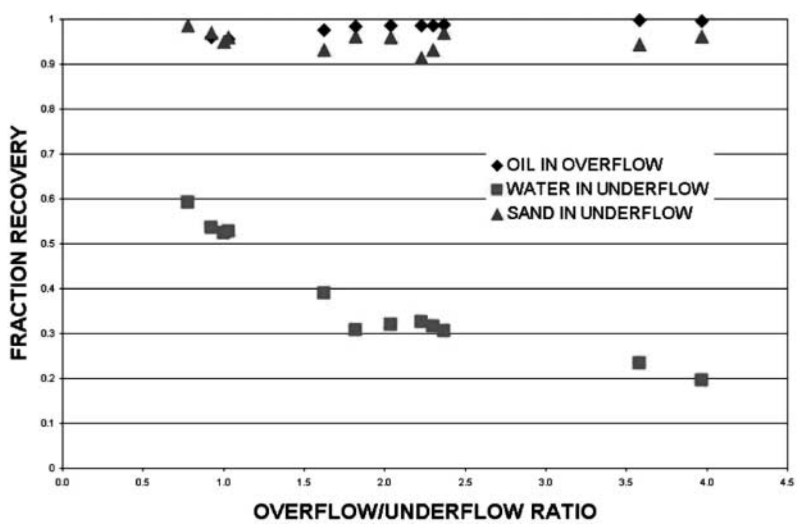

Figure 8. Fractional recovery of each component in the three-phase system in terms of overflow/underflow ratios (1/9 oil-to-water volume ratio).

overflow/underflow ratios, the water recovery in the underflow dropped to about 20%. The oil recovery in the overflow started at about 95% at low overflow/underflow ratios and increased to about 99% with increasing overflow/underflow ratio.

Shown in Fig. 9 is the fraction of the solids, oil, and water recovered in the appropriate streams, as a function of the overflow/underflow ratio. These data were for a feed ratio of 1/1 oil-to-water. The fraction of solids fed into the system that were removed in the underflow was consistently above 95%. With respect to the liquids, about 75% of the water went into the underflow at low overflow/underflow ratios. At high overflow/underflow ratios, the water recovery in the underflow dropped to about 40%. The oil recovery in the overflow started at about 80% at low overflow/underflow ratios and increased to about 99% with increasing overflow/underflow ratio.

Shown in Fig. 10 is the fraction of the solids, oil, and water recovered in the appropriate streams, as a function of the overflow/underflow ratio. These data were for a feed ratio of 9/1 oil-to-water. The fraction of solids fed into the system that were removed in the underflow was consistently above 90%. With respect to the liquids, about 55% of the water went into the underflow at low overflow/underflow ratios. At high overflow/underflow ratios, the water recovery in the underflow dropped to about 25%. The oil recovery in

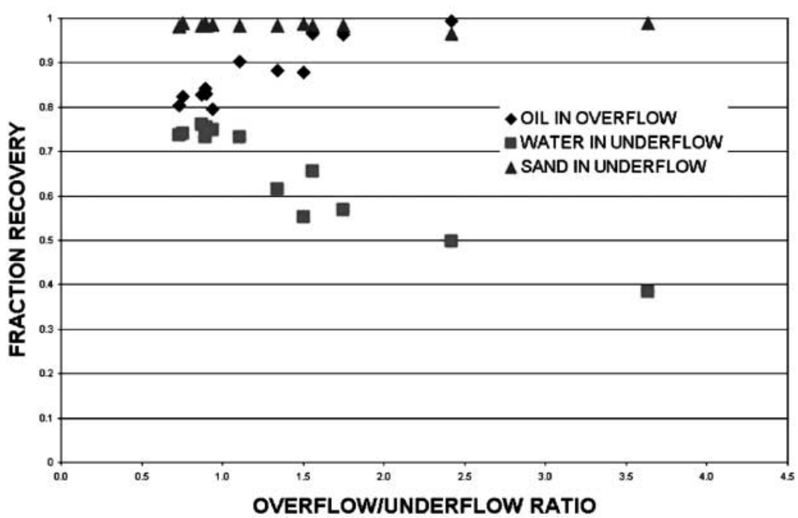

Figure 9. Fractional recovery of each component in the three-phase system in terms of overflow/underflow ratios (1/1 oil-to-water volume ratio).

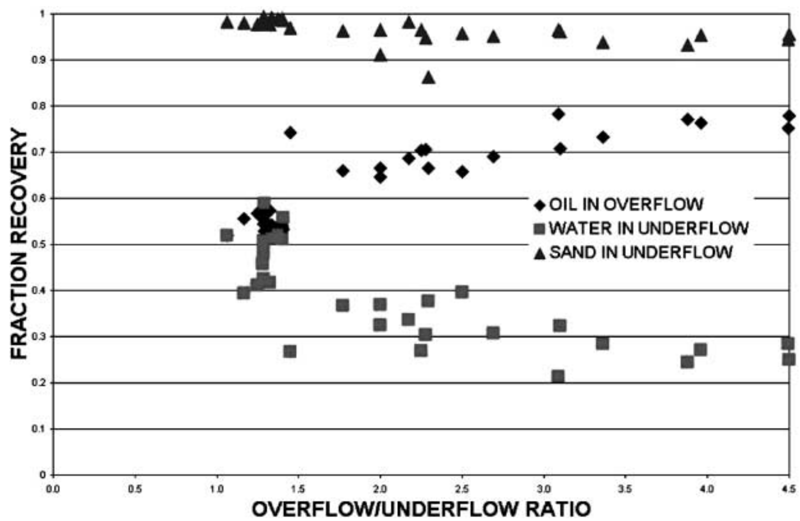

Figure 10. Fractional recovery of each component in the three-phase system in terms of overflow/underflow ratios (9/1 oil-to-water volume ratio).

the overflow started at about 55% at low overflow/underflow ratios and increased to about 80% with increasing overflow/underflow ratio.

This discussion indicates that an increase in the overflow/underflow ratio was desirable for the liquid separation but was a hindrance in the desired results of the solids separation. In general, as more oil was present in the feed, the recovery of the oil in the overflow decreased. Even more oil recovery may be possible at higher overflow/underflow ratio, but the current equipment limits this value to about 4.5 (when solids are present), due to plugging of exit lines that involve small streams.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results from this research show that solids can be effectively removed from a three-component feed by use of a hydrocyclone. When the feed was water continuous, the oil of the three-component system was nearly 100% recovered in the overflow. When the feed is oil continuous, some oil was lost in the underflow of the hydrocyclone. The water-continuous feed (separating oil from water) led to a very good liquid-phase separation efficiency (nearly 100%), but the liquid-phase separation efficiency was very poor for the oil-continuous feed stream (separating water from oil). By controlling the split, we were able to control the amount of liquid lost in the underflow of the hydrocyclone. The solids separation efficiency was accurately predicted for this system. This research supported previous research in this field.

Recommendations

For future research, it is recommended that different oils be used, including actual crude oil obtained from an oil well. A diverse particle size of solids should also be considered to further verify the prediction accuracy of the cutsize. Future research is planned for connecting the ORNL centrifugal separator to the hydrocyclone to demonstrate the completed apparatus.

NOMENCLATURE

Symbols

d_{50}	= cutsize	(m)
D_C	= hydrocyclone diameter	(m)
D_i	= diameter of the inlet of the hydrocyclone	(m)
E_{LP}	= liquid-phase separation efficiency based on the light phase	(−)
E_{HP}	= liquid-phase separation efficiency based on the heavy phase	(−)
n	= hydrocyclone specific parameter (normally assumed ∼0.6)	(−)
Q	= flow rate	(m^3/s)
Q_F	= flow rate of the feed stream	(g/s)
Q_O	= flow rate of the overflow stream	(g/s)
Q_U	= flow rate of the underflow stream	(g/s)
R_f	= volume ratio of feed to underflow	(−)
y_F	= mass fraction of the feed consisting of the light-phase liquid	(−)
Y_F	= mass ratio of solids to liquids in the feed	(−)
y_O	= mass fraction of the overflow consisting of the light-phase liquid	(−)
Y_O	= mass ratio of solids to liquids in the overflow	(−)
y_U	= mass fraction of the underflow consisting of the light-phase liquid	(−)
Y_U	= mass ratio of solids to liquids in the underflow	(−)

Greek Symbols

$1 - \phi_L$	=	fraction of the overflow stream that is at the feed composition	(−)
ϕ_{HP}	=	fraction of the underflow stream that is at the feed composition	(−)
α	=	velocity at the wall divided by the inlet velocity	(−)
μ	=	viscosity of the liquids	(kg/m-s)
Θ	=	included angle at cone apex	(rads)
$\Delta\rho$	=	density difference in the liquids	(kg/m^3)

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