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Modification of a Centrifugal Separator for In-Well Oil-Water Separation

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Abstract: A liquid–liquid centrifugal separator has been modified for possible application as a downhole method for separating crude oil from produced water. Centrifugal separators of various sizes (from 2- to 25-cm rotor diameter) have been built and operated over the past decades at various U.S. Department of Energy facilities. These units have several characteristics that make them attractive for downhole applications, including excellent phase separation, reliability in remote applications with $>$20,000 h of operation prior to maintenance, and the ability to handle high volumetric throughput with a very low residence time. These separators consist of a rotating cylinder in which the two phases are separated and a stationary housing that collects the separated streams. This paper discusses some of the aspects of the alterations required for downhole operation. Specifically, we discuss modifications of the exterior housing allowing for greater flow through the system. The system presented here improves the performance of a standard separator by 140%.

INTRODUCTION

Produced water is the largest generated waste stream by volume in the Gulf Coast region and is typically a mixture of formation and injection process water that contains oil, salts, chemicals, solids, and trace metals. In 1991,

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Louisiana generated over 1 billion barrels and Texas generated 7.5 billion barrels of produced water as a result of oil and gas operations. Young reported that more than 250 million barrels of produced waster are discharged each year to surface waters in both Texas and Louisiana (1).

When handling produced water in the future, two primary alternatives may be advantageous to (a) improve the treatment of produced water prior to surface or subsurface disposal or (b) reduce the volume of produced water by using downhole, or in-well, separation and reinjection.

Newer technologies considered by the industry for contaminant removal include hydrocyclones, reverse osmosis, membrane filtration, gas flotation, carbon adsorption, bioreactors, chemical oxidation, stripping/extraction, and UV oxidation. These processes are complicated and expensive, and several of these unit operations will be required to reduce the conventional, unconventional, and toxic pollutant concentrations to new discharge limits, which may include zero-discharge standards as suggested by Otto and Arnold (2).

Successful use of reinjection has increased in the last several years, but enhanced treatment is often required to remove oil and particulate matter to avoid damaging or plugging the rock formations. The suitability of produced water for reinjection is determined by the enhanced recovery process, the water quality, and the rock formation properties. Recent publications have reviewed the two hydrocyclone and gravity-based systems under current consideration (3, 4).

An ideal in-well separator should operate over a broad range of water-to-oil feed conditions. Over the life of a typical oil well, the ratio of water to oil will vary from near zero (nearly 100% crude oil) to near infinity (nearly 100% water, usually salt water). The current commercial technology uses two basic types; one uses hydrocyclones to separate oil and water and the other relies on gravity separation. In the commercial systems, hydrocyclones have been coupled with electric submergible (centrifugal) pumps, rod pumps, and progressing cavity pumps; gravity separators are coupled only with rod pumps according to Veil et al. (3).

The commercial hydrocyclone-based technology is based on the use of liquid–liquid hydrocyclones. According to Veil and coworkers, a liquid–liquid hydrocyclone has a typical length-to-diameter ratio of 20 to 40 (5). Veil, Langhus, and Belieu (5) and Verbeek, Smeenk, and Jacobs (6) also indicate that typical hydrocyclone-based technology is used for wells with water-to-oil ratios of 5 : 1 to 100 : 1 and typically produces fluids with water-to-oil ratios of 1 : 1 to 2 : 1 with oil concentrations in the separated water phase of $<$100 to 500 ppm. Fluids may be either pumped through or pulled through the hydrocyclone; the pump-through mode is more common; some installations have used a duel pumping system.

The gravity separator-based technology uses the oil-water separation as it exists in the underground structure and in the casing annulus. The most common gravity separator uses a rod pump modified to have two pumping chambers. The upper chamber is located near the oil-water interface and accepts a mixture of oil and water, which is pumped to the surface on the upstroke. The lower chamber is located below the oil-water interface so that primarily water enters and is injected on the down stroke. Veil et al. (5) report <100 ppm of oil in the discharged water from a gravity separator.

Veil and coauthors (5) report that the hydrocyclone and gravity separators have limited applicability because they cannot handle gas/oil/water mixtures, only remove 75% of the water per stage and cannot operate in the oil-rich phase or the transition phase so they are usually limited to water cuts greater than 65%. These limitations severely restrict the conditions under which existing downhole separator systems can be operationally and/or economically effective. They have only been economically deployed for on-shore applications where the costs for transporting and/or treating water is unusually high, and high water production limits the overall well production capacity (e.g., reducing the volume of water pumped to the surface can increase the incremental oil production). Better separations technologies will be required for applications where nonsurface treatment could make tremendous differences: zero discharge and off-shore platforms where water pumping costs are much higher than on-shore situations, and initial construction costs of separation equipment are extremely high.

Centrifugal separators of various sizes (from 2- to 25-cm rotor diameter) have been built and operated over the past three decades at the Savannah River Site (SRS), Argonne National Laboratory (ANL), and Oak Ridge National Laboratory (ORNL) for use in U.S. Department of Energy (DOE) applications (7, 8). These units have several characteristics that make them attractive for consideration in downhole separation of oil and produced water (9). These include excellent phase separation, reliability in remote applications with $>20{,}000$ h of operation prior to maintenance and the ability to handle high volumetric throughput with a very low residence time. In this paper we present results from modifications to the traditional separator that will have advantages in downhole operations.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

A model V-2 (2-in.-diameter rotor) centrifugal separator (CINC, Inc., Carson City, NV) equipped with a 1/6 HP motor was used for the benchscale tests. The standard housing that comes with this unit had been modified several times to improve the processing capacity. A brief schematic of the separator is shown in Fig. 1. The oil/water mixture enters the spinning rotor and the centrifugal force separates the oil and water, with water in the outer layer and oil in the inner layer. A column of air resides in the center of the rotor. The oil and water are pushed over their respective weirs and slung out from the rotor and into their respective collections rings that surround the rotor. The fluids leave their respective collection ring via gravity and flow-through exit ports. A more detailed drawing of this type of separator has been published by Leonard (7).

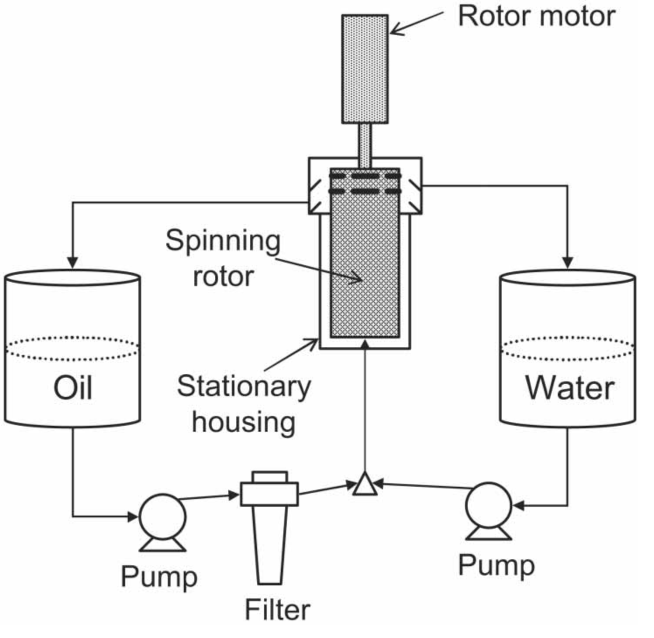

Figure 1. Schematic of centrifugal separator rotor and portions of its standard housing. The rotor spins while the housing with collection rings is stationary. Only a small section of the housing is shown.

The centrifugal separator was tested under a variety of operating conditions but always in a low mixing mode (10). In the low mixing mode, the organic and aqueous streams are vertically introduced at the bottom of the rotor (which is protected by a sleeve). In initial experiments, approximately 3 L each of tributylphosphate (TBP) and dilute nitric were used during a run (as a simple organic-aqueous test matrix). Later, 3 L each of Gulf of Mexico light crude oil and synthetic ocean water were used for the typical oil-water separation. In both cases, the organic and aqueous streams were continuously recirculated through the separator (Fig. 2). When crude oil was used, it was passed through a filter (Model: Zeta Plus UW, Cuno, Inc., Meriden, CT), which removed water and avoided build-up in the oil during longer runs. The organic and aqueous feed streams were mixed by a simple tee connection just before they entered the separator. The purpose of the low mixing mode operation and oil filtration to remove the water prior to (minimal) mixing was to simulate down-hole conditions, where it is believed that oil and water are fairly unmixed and enter the well in slugs. Further details about the operations can be found in the publications of Walker and Cummins (9) and by Klasson et al. (11).

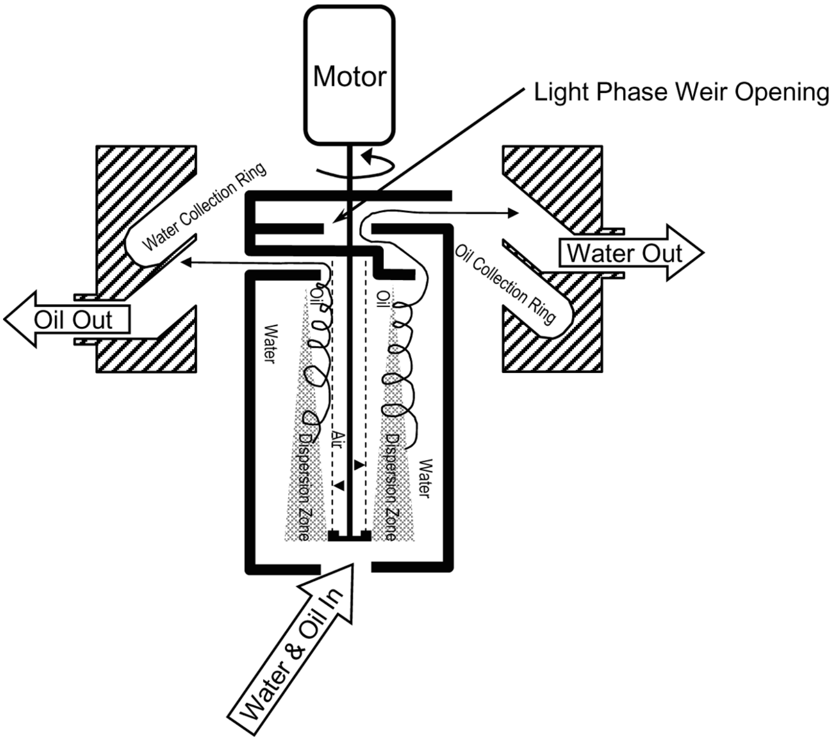

Figure 2. Experimental setup used in benchscale testing.

RESULTS AND DISCUSSION

The prototype separator unit used in our studies has been modified several times. The major modifications have been to the collection system (after organic-water separation) as this has been the limiting factor. The off-the-shelf system had an effective diameter of 3.5 in. (including the collection rings) for the 2-in. separator unit. This means that the collection system added at least 1.5 in. to the rotor diameter. For effective diameter, we are only considering the collection rings, and we do not take into account that exits protrude horizontally and pass beyond the rings. In the off-the-shelf system, the separated oil and water streams exit by the flow of gravity, through horizontal exits with small diameter. The capacity of the collection rings was also small. Early in our studies we found this arrangement to be limited, and the separated oil and water would not exit the unit sufficiently quickly to handle the flow. The housing was modified to include larger capacity collection rings and larger exits, but with the same general design as the original unit. This resulted in an effective diameter of 4.8 in. for the

2-in. rotor. The larger collection system allowed for a 60% higher volumetric flow rate, while maintaining the same separation efficiency. Though the modification improved the processing rate, it increased the effective diameter of the system, which is not desired in downhole operation.

In order to reduce the effective diameter, a new prototype housing was constructed which removed the separated streams through pumping. The additional pumps allowed narrow vertical exits from the system. The prototype housing was also designed in a fashion that allowed for the size of the collection rings to be altered.

The performance of the different systems can be seen in Fig. 3, where the results are expressed in term of flux. The flux is calculated from the volumetric flow rate of the streams divided by the cross-sectional area of the system (which is controlled by the size of the collection rings). Thus, the flux can be increased by increasing the volumetric flow rate or decreasing the diameter of the collection rings. The modified housing allowed for a higher volumetric processing rate (as mentioned earlier), but the flux remained the same or slightly lower (Fig. 3, processing a TBP/dilute nitric acid test matrix). This modification was still a success as it demonstrated that the housing design was an important factor to consider. As is noted in Fig. 3, the same modified housing separated oil and water phases in the Gulf of Mexico oil-water matrix with the same flux capacity as it separated the TBP/dilute nitric acid streams in the test matrix.

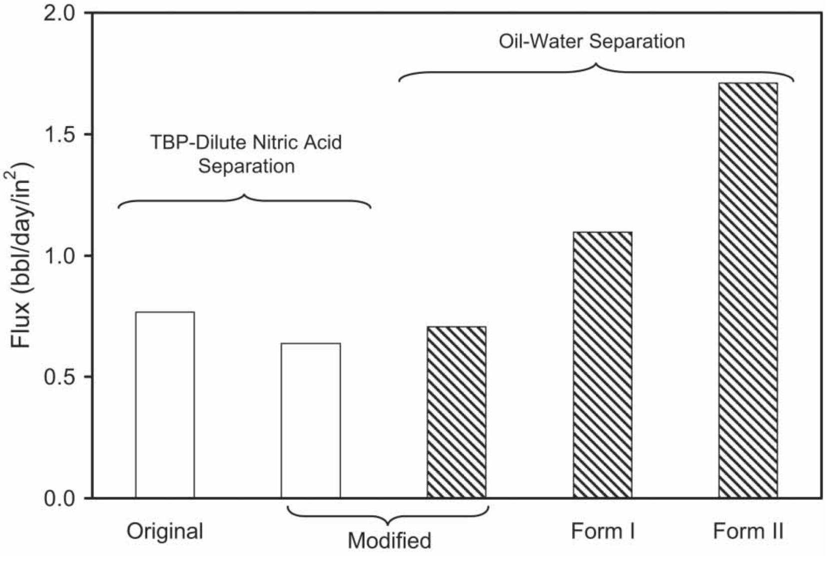

Figure 3. Processing rate using the 2-in. standard rotor with different housing configurations and different types of streams.

Figure 3 also showed results from experiments obtained using a new prototype housing (Form I and Form II). In the redesigned prototype housing, the volume of the collection rings is adjustable. The housing is cylindrical with a detachable cap (Fig. 4) to gain access to user-variable collection rings (Fig. 5). The exit ports are obviously less than optimal in their current configuration but extend down to the bottom of the separator unit.

The prototype housing (Form I, see Fig. 6) was designed to have the same approximate effective diameter as the original unit but with pumps to remove the separated streams. Note that the effective diameter is equal to the outside diameter of the collection rings. This design allowed for a higher flux than both the original and modified units (Fig. 3) because a greater volumetric flow could be processed. As the prototype housing allowed for changing the effective diameter (changing the size of the collection rings), we were able to further increase the flux by decreasing the ring size. The flux in Form II (Fig. 7) represents an increase in flux of 140% compared with the off-the-shelf unit with the original housing design. A schematic of the rotor and housing system is shown in Fig. 8 with simplified flow patterns for the two liquid phases.

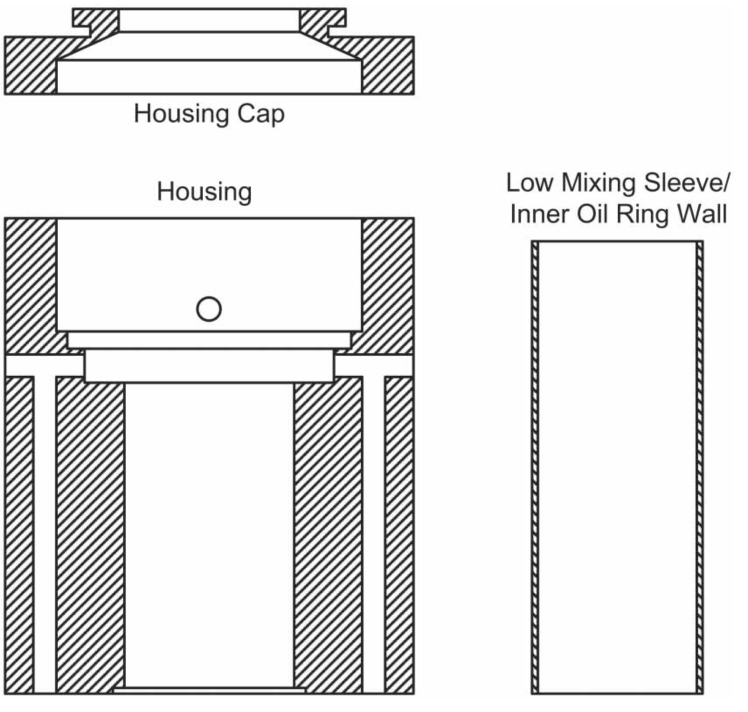

Figure 4. Schematic of prototype housing for a more symmetric unit.

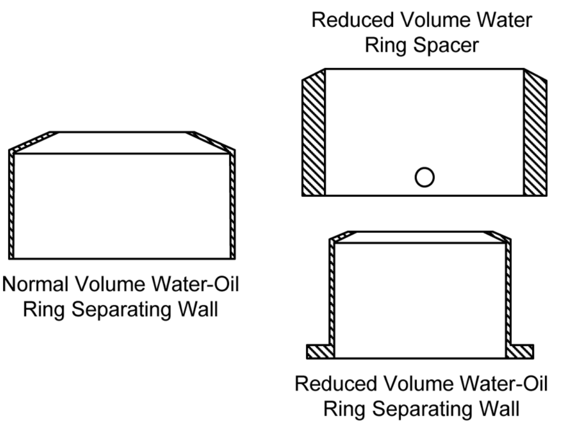

Figure 5. Housing inserts for control over collection rings diameter and volumes. The "normal insert" (left) results in a larger ring volume for the oil phase and a lesser ring volume for the water phase. The "reduced insert" (bottom right) reduces the ring volume for the oil phase and increases the ring volume of the water phase. The "spacer insert" (top right) may be used in combination with the "reduced insert" to keep ring volumes of oil and water phases small.

CONCLUSIONS

A centrifugal separator is currently being developed at ORNL that will extend the application of equipment that was developed for the nuclear industry to in-well recovery of oil. The purpose is downhole oil-water separation with

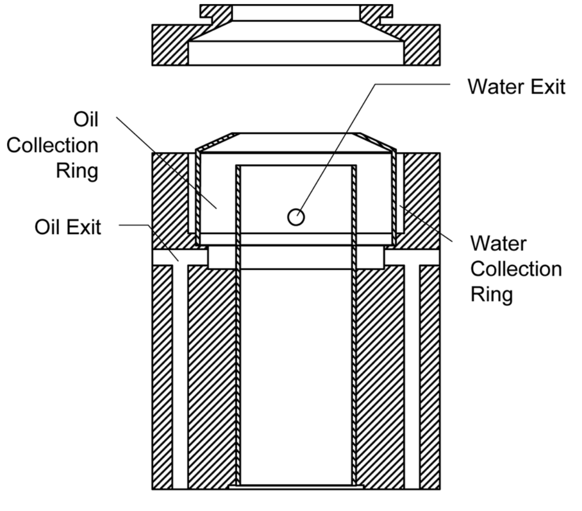

Figure 6. Form I prototype housing with a large-volume oil collection ring.

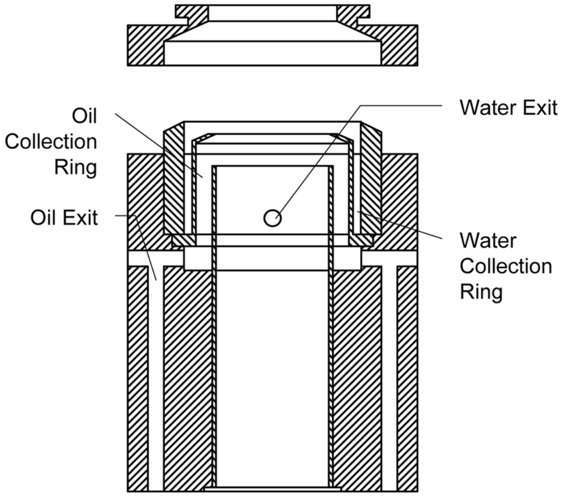

Figure 7. Form II prototype housing with low-volume collection rings.

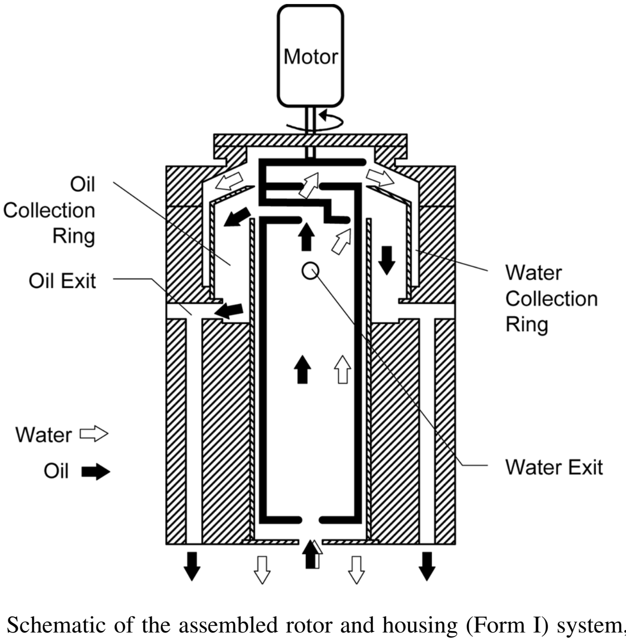

Figure 8. Schematic of the assembled rotor and housing (Form I) system, showing flows of the oil and water streams. The water and oil streams get separated in the spinning rotor and are "slung" out from the rotor and gathered in the collection rings. The exits from the oil collection ring are shown to the left and right. The two exits for the water collection ring are constructed in the same fashion but extend toward (and away from the reader, rather than to the left and right) then down.

in situ recycling of the produced water. Modifications to the rotor housing have increased the flux through the prototype centrifugal separator system by 140% over the original unit. This value does not necessarily represent the maximum performance but could possibly be improved upon through the further reduction of the collection ring volumes.

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