



OTC 13216

## Improving Process Efficiencies by Optimizing Fluid Hydraulics in Electrostatic Oil Dehydrators

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This paper was prepared for presentation at the 2001 Offshore Technology Conference held in Houston, Texas, 30 April–3 May 2001.

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### Abstract

The development of computational fluid simulation software for the desktop computer when combined with simple calculations and model testing for confirmation provide process equipment designers with exceptional tools to advance the performance of oil production equipment. Specifically, this article detail the CFD models, calculations and testing methods employed to identify and improve the vertical fluid hydraulics in horizontal vessels. CFD simulations provided insight into the mechanisms responsible for both the uniform distribution and collection of oil/water production fluids. Simple calculations provided confirmation of uniform longitudinal distribution through perforated spreaders and collectors. Simple hydraulic simulations using a basic “water-table” provided visual confirmation of the CFD results as well as allowing “fine-tuning” of the resulting design changes. These new developments have permitted significant increases in vessel throughput without sacrificing performance.

### Introduction

As the world’s oil production increasingly consists of heavier, viscous oil, the difficulty of dehydrating them also increase. Not only must the equipment designers rely on more aggressive electrostatic treatment methods; they must also examine the fundamentals of fluid hydraulics within the process vessel. It has been assumed that uniform fluid hydraulics in large horizontal vessels operating with vertical fluid movement such as oilfield electrostatic treaters was routinely achieved. However, with CFD simulations and lab experiments it has been determined that flow uniformity is not easily achieved.

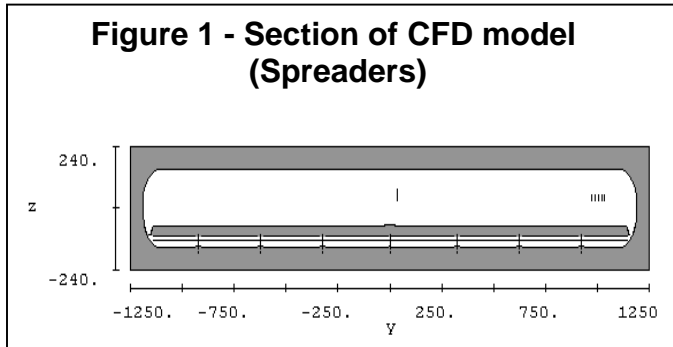
An electrostatic dehydrator works by establishing an oil/water interface at approximately 30% of the vessel diameter. A set of longitudinal pipes is installed slightly above the interface. These pipes, perforated along their length on both sides with uniformly spaced orifices, introduce the oil/water mixture into the vessel. The flow exits horizontally from these orifices and gradually turns to flow vertically upward toward the collector located in the top of the vessel. As dispersed water droplets within the mixture coalesce to larger sizes, they settle against the rising oil flow. The oil is dehydrated as the entrained water is first coalesced by the electrostatic field and then separated by gravity. The overhead collector consists of a pipe arranged longitudinally along the top of the vessel. Orifices are either placed on both sides or the top of the collector pipe and arranged to achieve uniform collection of the rising oil.

After CFD software became readily available it was easy to mathematically simulate the fluid hydraulics under the variety of operating conditions experienced during operation. These simulations could also include conditions encountered in dehydrators installed on FPSO facilities. While CFD simulations can confirm the movement of production fluids through a typical electrostatic dehydrator, it also permits the designer to quickly investigate alternative fluid control methods. It is prudent to confirm the CFD results by visual confirmation whenever possible until the designer is comfortable with the CFD simulations. Surprisingly, the first spreader and collector designs thought to produce uniform fluid distribution were, in fact, responsible for the poor distribution observed.

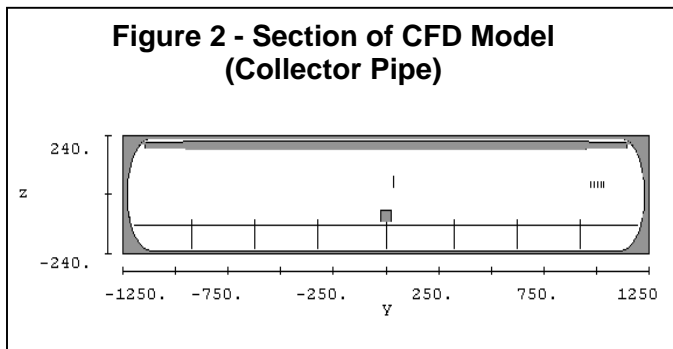
### Computational Fluid Dynamics

Numerous software packages are now available to the staff engineer wishing to examine a wide variety of physical and chemical effects. For this study, Flow 3D by Flow Sciences, Inc. of Los Alamos, NM was used. A three-dimensional simulation of a 14’ OD x 70’ S/S electrostatic treater was constructed as shown in Figures 1 and 2. The spreader system consists of 4 pipes spreading longitudinally from a central inlet manifold housing. These pipes contain equally spaced orifices on both sides to achieve uniform flow distribution both longitudinally and transversely within the process vessel.

These pipes are located about 3 feet from the bottom of the vessel. A single longitudinal pipe collector is located near the top of the vessel. A central outlet nozzle is located near the center of the vessel. The collector pipe contains orifices on

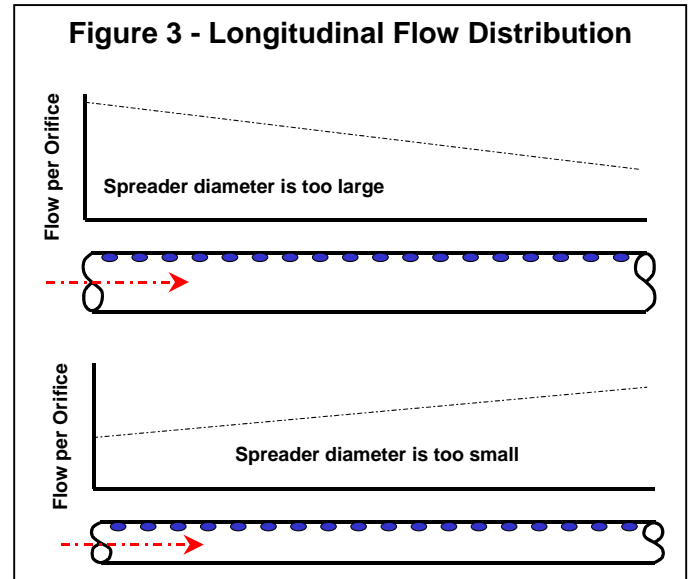


both sides to achieve uniform collection of the dry oil. The collector pipe stops several feet short of the head seam on both ends. Figure 2 shows the original collector (larger diameter), and the extensions (smaller diameter) added later to the ends of the original to correct the collection deficiency.



This vessel was designed to process a heavy crude oil at a design rate of 60,000 BOPD. The oil contains over 10% water for a minimum inlet flow of about 66,000-BPD. Each of the eight spreader branches handles about 8350 bpd. Assuming the flow is uniform and vertical at the center of the vessel, the rate is about 115 bpd /sq. ft. based on the maximum horizontal cross-sectional area.

CFD software permits the user to consider the influence of a variety of oil properties including density, viscosity, surface tension, and drag coefficients on the flow distribution and collection. For this example, the prominent variables were considered to be the oil density of 0.88 gm/l and the viscosity of 0.16 Stokes. To achieve reasonably quick solutions, the

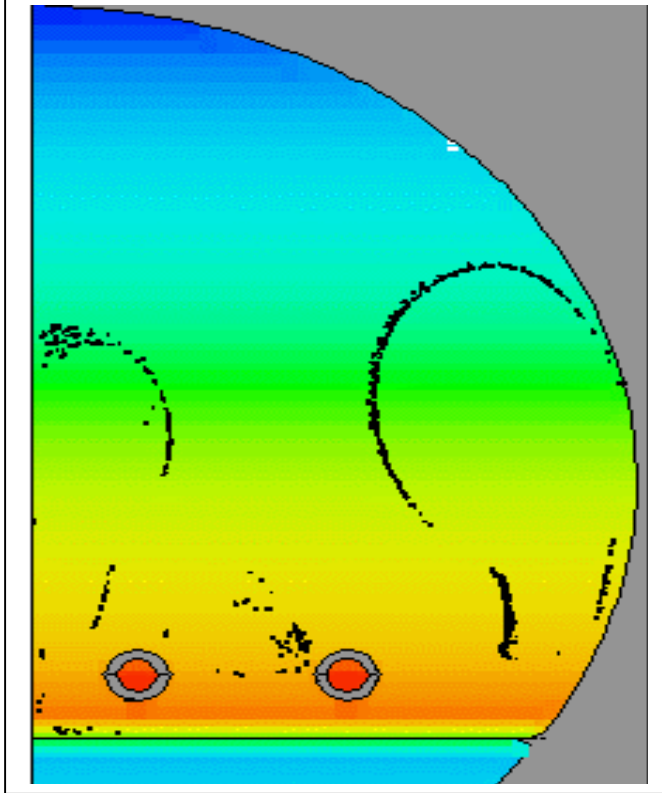


CFD model as shown in Figures 1 and 2 was constructed with a relatively large mesh size resulting in a model of 180,000 cells. Each cell representing about 0.01 cu ft of vessel volume. The simulation began with the vessel filled with oil and a stationary water level established just below the spreader pipes. A simple steady-state simulation was performed for a period of about 100 seconds. Actual computing time for each simulation was around 24 hours.

Figure 3, a section of a spreader pipe oriented along the axis of the vessel, shows the influence of pipe size on longitudinal distribution uniformity. When the spreader diameter is too large the flow from the orifices nearest the inlet are greatest. If the diameter is too small the high velocity forces flow to exit the far end of the spreader. If the diameter is extremely small the frictional losses may prevent the flow from reaching the last orifices, In either case, the longitudinal mal-distribution may be as much as 25% resulting in poor dehydration performance.

Figure 4, a transverse cross section of half of the vessel taken near the longitudinal center, shows an even greater degree of mal-distribution. Prior to starting the CFD simulation, a row of mass-less particles were evenly placed along the centerline of the vessel. As the particle movement shows the majority of the flow is along the shell and up the center with a significant downward flow in the center of the plotted area. About 75% of the process flow circulates downward through 50% of the horizontal cross-section. The resulting upward velocity is nearly 300% of the theoretical design velocity. Therefore, the majority of the process fluids are treated by the weakest electrostatic field adjacent the walls at velocities nearly three times the design.

**Figure 4 - Particles Indicating Fluid Flow**



By applying a simple Bernoulli energy balance repetitively between orifices, it is possible to determine the degree of maldistribution between the first and last orifice on a single spreader branch. With the aid of engineering software, it is possible to determine the optimum diameter and orifice combination for any process flow condition. It is generally known that when oil and water are vigorously mixed the resulting mixture viscosity increases significantly. The best distributor design is obtained when this mixture viscosity is used to determine the pressure losses between and across orifices.

An appropriate criteria is to design the spreader to achieve a ratio between 0.95 and 1.05 when the flow rate from the first orifice is divided by the flow rate from the last orifice. In some applications a wide variety of spreaders will meet this criteria. The optimum design may then consider cost, construct-ability, functionality and flexibility.

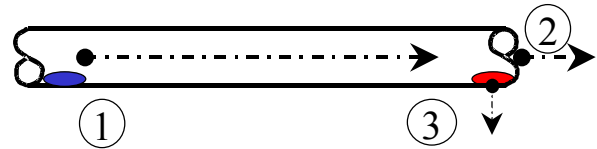
**Energy Balance**

Equations 1,2 and 3 establish the energy and mass balance as well as the velocity through the orifice. Since the L/D ratio of spreaders is typically high and the flow velocities are low, it is essential to consider the effect of kinetic energy on the flow distribution when designing an efficient spreader. As the

Bernoulli energy balance indicates, the reduction in kinetic energy at 2 must be equaled by an increase in the potential energy to maintain the required energy balance. Therefore, immediately following each orifice there is an increase in the static pressure at P<sub>2</sub>. This increase in potential energy provides additional pressure to aid in distributing the flow to the end of the spreader.

In it's simplest form the energy balance equates the total (static + kinetic) energy at 1 with the total energy at 2 less the frictional losses along the spreader pipe between 1 and 2.

**Equation 1 - Bernoulli Energy Balance**



$$\frac{P_1}{\rho} + \frac{v_1^2}{2g} = \frac{P_2}{\rho} + \frac{v_2^2}{2g} + \frac{\Delta P_{1-2}}{\rho}$$

Where:

- P<sub>1</sub> = Static pressure after first orifice
- v<sub>1</sub> = flow velocity after first orifice
- P<sub>2</sub> = Static pressure after second orifice
- v<sub>2</sub> = Flow velocity after second orifice
- ΔP<sub>1-2</sub> = Friction losses in pipe between orifices
- ρ = Fluid density

**Mass Balance**

The associated mass balance is also quite simple. The volumetric flow rate at 1 must be equal to the sum of the flow rate across the orifice at 3 and through the pipe at 2. In most applications A<sub>1</sub> and A<sub>2</sub> are equal since the pipe size is not enlarged or reduced.

Where:

- A<sub>1</sub> = Pipe flow area at first orifice
- A<sub>2</sub> = Pipe flow area at second orifice
- A<sub>3</sub> = Orifice flow area
- V<sub>3</sub> = Flow velocity from second orifice

**Orifice Velocity**

Finally the flow rate across the orifice is determined by the pressure differential between, P<sub>2</sub> and the vessel operating pressure, P<sub>0</sub>. For optimum performance high pressure drops across the orifices must be avoided. In other words, large orifices are required to reduce the orifice velocity and thereby the pressure-drop. However, the orifice size must be balanced

with the orifice count to achieve homogeneous distribution along the longitudinal axis of the vessel. Common orifice sizes range from ½” to 1” for most oil dehydration applications. Although the orifice velocity may be low, the flow can be assumed fully turbulent permitting a simple equation for

### Equation 3 - Orifice Equation

$$V_3 = 1830 \sqrt{\frac{\Delta P_{2-0}}{\rho}}$$

determining the orifice velocity to be used.

Where:

$\Delta P_{2-0}$  = differential pressure across the orifice

When designing for an optimum spreader, several parameters are important. Small pipe diameters create high liquid velocities that reduce the static pressure available to deliver the flow across the orifices; the result is less orifice flow near the inlet end and more flow at the closed end of the spreader. Conversely, low velocities permit the majority of the flow to exit the orifices nearest the inlet, failing to distribute fully to the end of the spreader. Typically, the spreader velocity and orifice should be around 1.5 fps for optimum distribution. However, even at 1.5 fps the kinetic energy contained in the orifice flow is significant enough to dominate the distribution pattern. It was readily observed that flow exiting a single orifice at 1.5 fps could travel unabated to the opposite side of the vessel. As a consequence of this kinetic phenomenon the oil/water mixture follows the vessel wall rather than distributing uniformly below the electrodes.

### Momentum Control

The energy of the oil/water mixture is sufficient to carry each orifice jet to the opposing wall where it is directed upward by the curvature of the vessel. As the jet moves through the surrounding fluid it creates an increasing cone of fluid as it “drags” adjacent fluid along its path. Further investigation indicated that lighter fluids, those with less viscous drag, tend to remain as a stream while the heavier fluids with more viscous drag tend to initiate involvement of adjacent fluid and disburse more quickly. In both cases unwanted parasitic circulation resulting from the orifice jets lead to the gross counter-flow mentioned earlier. The results were not only fluid flow in the wrong direction through the electrodes, but a reduction in the apparent vessel residence time of about 45%.

Attempts to control this jet penetration by orifice size,

pressure drop, orientation and location were unsuccessful. The only effective method of reducing the momentum of each orifice jet was to capture them and then redirect them into the vessel.

### The Problems

Employing CFD simulations, water-table testing and energy balance calculations to evaluate the original spreader and collector performance, the following conclusions were drawn.

1. Longitudinal distribution along each of the four spreader ligaments was within the +/- 5% for efficient performance.
2. Each of the four ligaments distributed an equal volume of fluid within the same 5% goal.
3. Flow momentum from each orifice controlled the transverse distribution of the spreaders.
4. Uniform longitudinal collection in the outlet was achieved to within the +/- 5% goal.
5. The short collector length contributed to the maldistribution of the longitudinal flow.

### The Solution

Developing a solution involved additional CFD simulations and water-table confirmations. The goal was to achieve a uniform vertical velocity across the centerline of the vessel just below the electrodes. It was obvious from the earlier work that the original spreader and collector designs could be greatly improved. Furthermore, with CFD simulations a variety of options could be investigated at a modest cost.

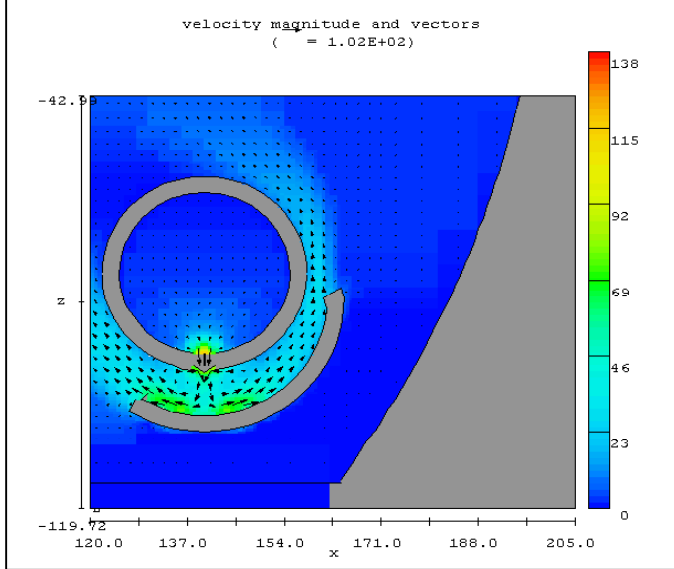
### Spreaders

It was reasoned that if the spreader exit velocity could be reduced and the stream broadened better distribution would result. Since the optimum electrostatic treatment is achieved just above the center of the vessel, the placement and orientation of the spreader was determined to obtain uniform velocity in this region of the vessel. It was also apparent that the streams would have to be aimed toward the electrode region instead of allowing the vessel wall to direct the flow. CFD modeling, confirmed with wave table simulations, shows that spreader placement was critical to achieving this uniform flow.

These goals were accomplished, as shown in Figure 5, by using a 120° pipe shroud around the bottom of two spreader pipes. All orifices were located on the bottom of the spreaders allowing their discharge to be captured by the shroud. Once the oil/water mixture hits the shroud it is spread over a wide area and the velocity is significantly reduced. The shroud then redirects the mixture around the pipe spreader and into the vessel. The mixture exits the gap between the shroud and the spreader pipe at a low velocity.

The width of the gaps, or slots, between the pipe and deflector determines the velocity at which the fluid enters the resident bulk fluid body.

**Figure 5 – Pipe / Deflector Spreader**

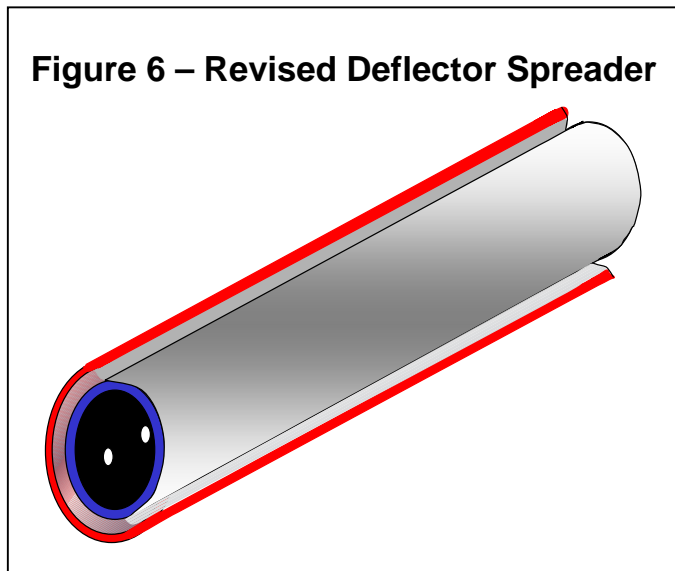


This spreader design reduces the kinetic energy of each orifice by 99% or more.

The spreader, shown in Figure 6, must be installed just above the oil/water interface and slightly inside the vessel wall. The shrouds are oriented to direct the flow toward the collector. Angular orientation of the orifices, deflector arc and pipe combined with the concentricity of the pipe and deflector aimed the process fluid toward the electrodes. When properly designed, this spreader arrangement can be oriented so fluid bypassing the ends of the electrodes at the vessel wall can be stopped or even reversed. Velocities across the remainder of the electrode region are nearly uniform.

Figures 7 and 8 provide before and after comparisons of

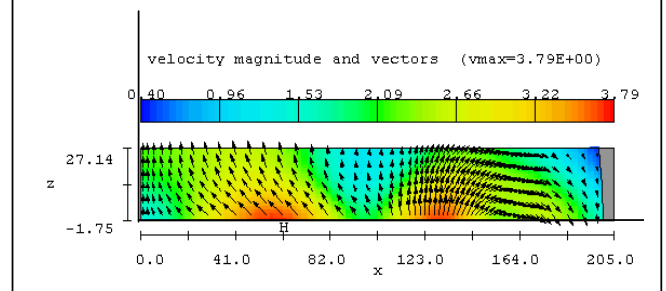
**Figure 6 – Revised Deflector Spreader**



fluid control between the original and revised designs. To demonstrate the vertical advancement of fluid toward the electrodes, velocity vectors were plotted in the region above the vessel horizontal centerline ( $Z=0$ ) and right of the vertical center.

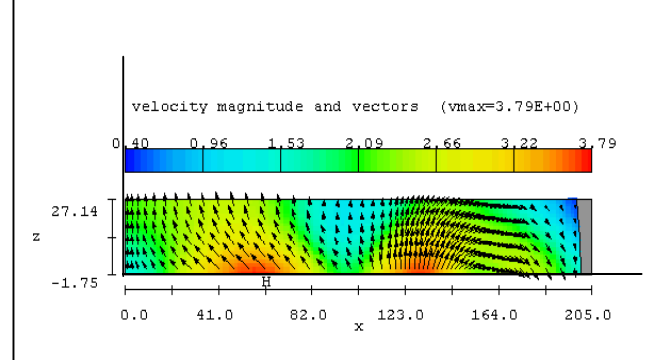
The original spreader performance shown in Figure 7 shows high velocities near the vessel wall and up the center of the vessel. Flow between these streams is in the downward direction, the wrong way. This indicates a gross circulation of fluid which reduces dehydration efficiency and residence time. Note that the velocity across the centerline ranges from an upward 11.2 cm per second to a downward 3 cm per second. It also indicates a considerable volume of fluid skirting by the ends of the electrode in the weaker portion of the electric field

**Figure 7 - Revised Pipe/Deflector Design**



In revised spreader performance shown in Figure 8 achieves a fluid velocity at the centerline ( $z=0$ ) ranging from about 2.0 cm per second to 3.79 cm per second with flow reversed only near the vessel wall. This reverse flow eliminates fluid bypassing the electrodes. While not perfect, this represents a significant increase in distribution efficiency and actual retention time.

**Figure 8 – Revised Deflector Spreader**

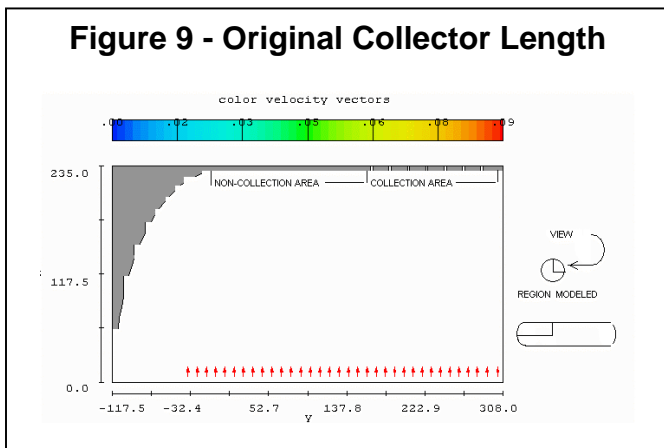


Experiments were conducted using a simple water table to confirm the CFD results observed. The water flow across the table when injected with a dye permitted a rapid visualization of the flow patterns. The results of the water table experiments confirmed the CFD results with surprising accuracy.

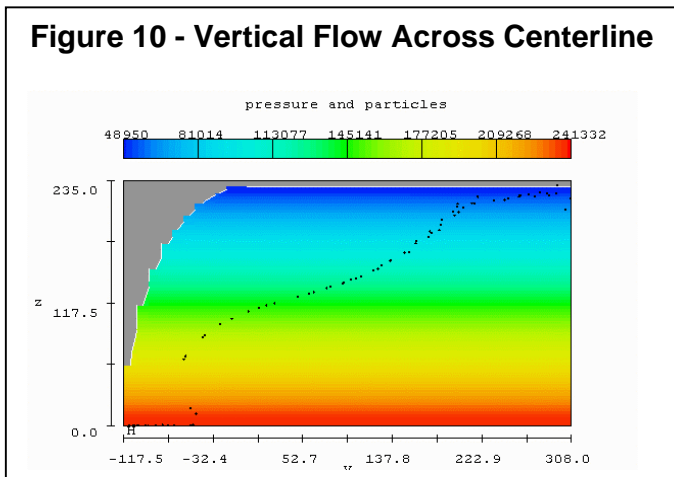
**Collector**

The CFD results showed the collector located in the top of the vessel influenced the direction of the flow well below the electrodes. Since the collector was 6 feet shorter than the vessel the flow was not processed effectively in the heads. Furthermore, the low vertical velocity in the head area results in an increased velocity near the center of the vessel. Not only was the collector length important but, similar to the spreader, the size of the collector pipe and orifices was also critical to maintaining a uniform flow per orifice.

Figure 9 shows the CFD model used to determine the influence of the collector. To separate the collector performance from the spreader performance, the vertical velocity was assumed to be uniform across the centerline of the vessel. The overall collector length was about 15% shorter than the vessel length. Figure 9 shows where the collector stopped in the original design.



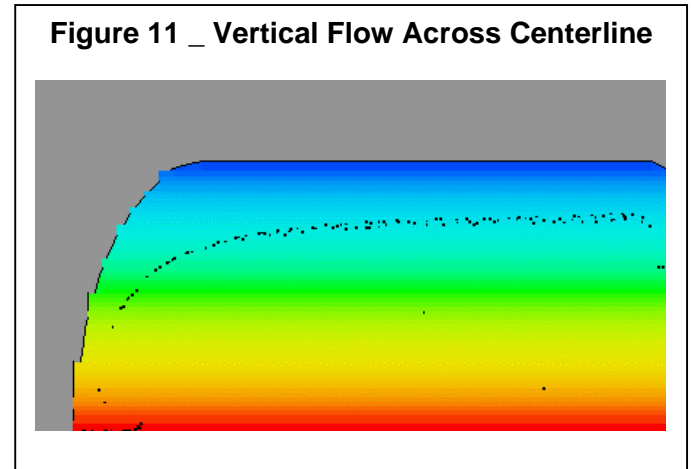
Using mass-less particles to trace the velocity profile, the CFD results in Figure 10 show the flow preferentially moving toward the collector at a rate nearly twice as fast as the flow



rate near the heads. The result is reduced gravity separation performance due to the increased velocity over a significant

area of the vessel. Estimated performance degradation is expected to be about 15%.

After modifying the collector by simply extending it into the head, Figure 11 shows a significant improvement in distribution. The particle movement is nearly uniform along the entire length of the collector.



**Conclusion**

When effective flow distribution in both the longitudinal and transverse direction is achieved from the spreader and a properly sized full length collector is used the resulting improvement in process performance can be significant.

In the example used for the article, the energy balance, CFD calculations and water-table modeling provided valuable insight into the process flow patterns within an electrostatic dehydrator. Not only did the results permit a significant improvement in the vessel flow distribution, it dispelled years of false conclusions regarding the validity of earlier distribution and collection systems.

The modifications described have been applied to the dehydrator studied for the article. To date the capacity of the unit has been increased by 25% and it is expected that the equipment will continue to meet the required process specification at rates to 166% of the original processing rate.