LABORATORY TESTED DOWNHOLE GAS-SOLIDS-LIQUID SEPARATOR

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ABSTRACT
This paper reviews the features and laboratory tests for a unique downhole gas-solids-liquid separator that has been designed. The objective of this project was to develop a gas separator that would perform efficiently at high fluid flow rates and could be also used in combination with a solids separator. The device attaches to the inlet of progressing cavity and beam pumps. With electrical submersible pumps a shroud is used. Scale-model tests were used to evaluate the design at high fluid flow rates.

INTRODUCTION
Downhole gas-liquid, solids-liquid, and gas-solids-liquid separators are used in many oil and water wells. Removing the gas from the pumped liquid improves the downhole pump efficiency and the resulting production rate. Keeping the solids out of the pump increases the life of the pump and eliminates plugging problems.

Poorboy gas anchors are effective with beam pumps in gassy wells if the flow rates aren't too high. Combined with solids separators, as shown in Figure 1, these separators are also effective in keeping sand and other solids out of the pump. Removing the gas before the solids often improves the efficiency of the solids separator. Solids can be removed at much higher flow rates than gas with this configuration. The use of poorboy gas anchors are restricted to even lower flow rates with continuous flow pumps.

Running the pump intake below the casing perforations is also an effective way to keep gas out of the pump when the flow down the casing annulus to the pump intake is below ½ foot per second. However, even when the flow velocities down the annulus are low, it is often undesirable or impractical to run the pump intake below the perforations.

This paper discusses a downhole separator design that is being developed to efficiently separate gas and solids, or gas only, from liquids in high-flow-rate wells. The concept utilizes centrifugal forces, downward liquid flow, gravity forces, buoyancy forces, and an inlet strainer to obtain the desired results. Moving parts are not used to produce the centrifugal action.

DESCRIPTION OF SEPARATOR
The separator design that was evaluated is shown in Figure ***2***. It attaches to the intake of progressing cavity and beam pumps. **A** shroud is used with electrical submersible pumps. The separated gas is released back into the casing annulus where it can rise to the liquid surface in the well. The separated solids are collected in a mud anchor that is attached to the lower end of the unit.

The main components of this device include a separator body, an inlet strainer, a gas spiral, a gas separation chamber, a gas reservoir, gas outlet ports, a check valve, a solids spiral, a solids separation chamber, and an outlet liquid flow tube.

The strainer has small inlet holes in it to prevent many of the large gas bubbles from entering the separator. The deflected bubbles float up the casing annulus to the fluid surface. Small holes deflect more gas than large ones, but the openings have to be large enough to pass solids without plugging the strainer.

The fluid flows down through the stationary gas spiral. The spinning motion that is produced by the spiral moves all the bubbles in against the outlet flow tube in the gas separation chamber. In **this** position, the gas forms large bubbles that separate from the downward fluid flow and float up into the gas reservoir.

The gas collects in the gas reservoir above the gas separation chamber until the gas pressure is sufficient to open the check valve. The pressure increases as the height of the gas column increases. The pressure required to open the check valve is equal to the pressure loss through the strainer holes and the gas spiral. When the check valve opens, the gas can escape back into the casing annulus. The gas bubbles then float to the liquid surface if the downward liquid velocity in the annulus is less than ½ foot per second.

In some designs, the check valve can be replaced with a properly sized orifice. The orifice restricts the liquid velocity down through the gas reservoir enough to let the gas bubbles rise. When the gas column in the gas reservoir develops enough pressure, the gas can escape back into the casing annulus.

The gas-free liquid flows from the gas separation chamber down through the solids spiral. The vortex flow produced below the solids spiral forces the solids out against the body wall while the gravity forces move them into the mud anchor. The clean fluid reverses direction in the vortex flow and moves up the outlet flow tube to the pump. Any dissolved gas that is released due to pressure loss in the solids spiral and the outlet flow tube will reach the pump.

TEST SETUP

A schematic of the laboratory test setup that was used to evaluate this gas separator design is shown in Figure 3. The device was tested at a reduced scale to keep the required tube sizes and fluid flow rates small. All of the tubing was clear so that the bubble motion could be observed. The control valves, pressure gages, and flow meters that were used are not shown in the sketch. Water and air at approximately 90° **F** were used for these tests.

MODEL SCALING

The model variables were sized by using conventional scale-model techniques. The model was geometrically similar to the full-scale design. That is, all linear dimensions were reduced by the same amount and all angles on the model were the same as on the prototype. A scale factor of 0.417 was selected for the 2.375-tubing-size prototype. With this scale factor, for example, a dimension of 3 inches on the prototype became 1.25 inches on the scale model.

In addition to the geometry of the design, the main variables that were assumed to affect the performance of the separator were accelerations, times, velocities, flow rates, densities, pressures, forces, surface tensions, and viscosities. Since the acceleration of gravity was the same for the scale model as for the prototype, and the water used for the model test was assumed to have the same density as the prototype liquid, the scaling factors shown in Table 1 were derived for these variables.

The model flow rates were reduced by a factor of 0.1 12 for the model accelerations to equal the full-scale accelerations. These flow rates reduced all the velocities by a factor of 0.646. Times were also reduced by a factor of 0.646. The fluid was moving slower, but it didn't travel as far so events happened in less time. The resulting pressures were reduced by a factor of 0.417, which in turn, reduced the forces on the model components by a factor of 0.073.

The liquid surface tension (force per unit length) should have been reduced by a factor of 0.174 and the viscosity by **a** factor of 0.269 to represent water in the prototype at 90" F. Since surface tension and viscosity were not reduced the water used in the model tests represented a prototype fluid with a surface tension 5.747 times larger than water and 3.717 times more viscous as listed in Table 2.

Since air was used, the gas properties were not scaled for any typical well gas. The actual gas properties such as densities and specific heat ratios, for example, were only roughly approximated by using air.

TEST RESULT

The scale model was tested at water flow rates from zero to 1600 barrels per day with airflow rates as large as 36,000 cubic feet per day. These numbers are equivalent full-scale values for a separator sized to fit on 2.375 tubing in 5.5-inch casing.

Over the complete range of air and water flow rates, no air bubbles were observed going into the water pump. In all cases, 100% of the air was removed from the water before it reached the water pump.

Normally, most of the air traveled up the casing annulus without entering the separator. All the bubbles that did enter the separator joined to form large bubbles wrapped around the outlet tube in the gas separation chamber. The large bubbles then moved up into the gas reservoir. When the height of the air column became large enough to open the check valve, the air was exhausted into the casing annulus. Once back in the simulated casing annulus, the air bubbles floated up to the water surface.

All of the air flowed quickly from the gas reservoir into the casing annulus when the water pump was stopped. When the pump was started again, the air collected in the gas reservoir until the required pressure was developed to open the check valve.

EXPLANATION OF RESULTS

Several features worked together to produce the outstanding results. The direction and magnitude of the forces on the bubbles, which are illustrated in the cutaway view in Figure 4, help to explain why all of the air was removed from the water. The arrows labeled with C and c represent the centrifugal forces on the large and small bubbles. The D and d arrows represent the drag forces produced by the fluid flow, while the B and b are the buoyancy forces produced by gravity.

First of all, the inlet strainer restricted the amount of air drawn into the separator with the water. **As** a result, the volume of air that had to be removed in the separator was greatly reduced. **A** large percent of the air simply went on up in the simulated casing annulus to the water surface.

The next important action took place after the flow went down through the gas spiral. The spinning motion produced by the spiral quickly moved all of the bubbles inward against the outlet tube at the center of the unit. In this position with the relatively large centrifugal forces on the bubbles, all **of** the bubbles combined into large torus-shaped bubbles that wrapped around the outlet flow tube. These torus-shaped bubbles had fluid-flow drag forces on only one side. In addition, the bubbles were in a low downward velocity area. **As** a result, the bubbles soon became large enough to resist the fluid-flow drag forces and move up into the gas reservoir.

The ratio of the gravity-buoyancy force to the fluid-drag force becomes larger as the bubble size increases. For example, water-flow velocities as small as 0.1 foot per second will drag small 0.06-inch-diameter air bubbles down against buoyancy forces. Larger 0.3-inch-diameter bubbles require flow velocities over 0.6 of a foot per second to drag them down with the flow.

CONCLUSION

Based on scale-model laboratory tests with air and water at 90° F:

1. The downhole separator design discussed in this paper is capable of removing a large percent of the free gas from production liquids in high-flow-rate wells.
2. This gas anchor can be operated with the fluid inlet above the casing perforations, and within or below the perforations if the liquid velocity down the casing annulus between the gas outlet ports and the fluid inlet strainer is less the 1/2 foot per second.
3. This device can be assembled and used as a gas-soilds-liquid separator, a gas-liquid separator, or a solids-liquid separator.

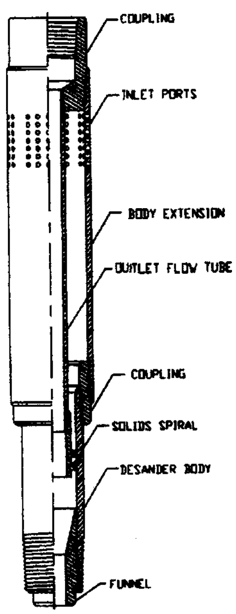

FIGURE 1
MEDIUM-FLOW-RATE
POORBOY GAS ANCHOR
WITH
SANDTRAP SEPARATOR

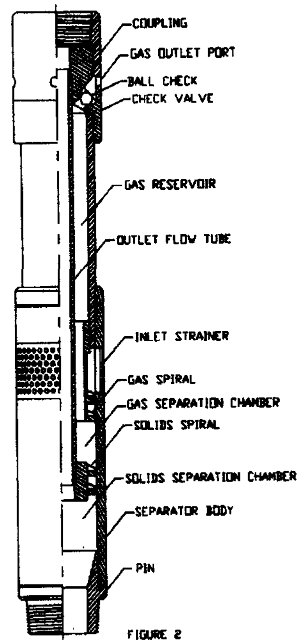

FIGURE 2
HIGH-FLOW-RATE
SPINNER GAS SEPARATOR
WITH
SANDTRAP DESANDER

PROTOTYPE TO MODEL SCALING		
VARIABLE	SCALING EQUATION	SCALING FACTOR
LENGTH	S*	0.417
ANGLE	1	1
ACCELERATION	1	1
TIME	S^0.5	0.646
VELOCITY	S^0.5	0.646
FLOW RATE	S^2.5	0.112
DENSITY	1	1
PRESSURE	S	0.417
FORCE	S^3	0.073
VISCOSITY	S^1.5	0.269
SURFACE TENSION	S^2	0.174

* S=MODEL LENGTH/PROTOTYPE LENGTH

TABLE 1

MODEL TO PROTOTYPE SCALING		
VARIABLE	SCALING EQUATION	SCALING FACTOR
LENGTH	1/S*	2.398
ANGLE	1	1
ACCELERATION	1	1
TIME	(1/S)^0.5	1.548
VELOCITY	(1/S)^0.5	1.548
FLOW RATE	(1/S)^2.5	8.929
DENSITY	1	1
PRESSURE	1/S	2.398
FORCE	(1/S)^3	13.699
VISCOSITY	(1/S)^1.5	3.717
SURFACE TENSION	(1/S)^2	5.751

* S=MODEL LENGTH/PROTOTYPE LENGTH

TABLE 2

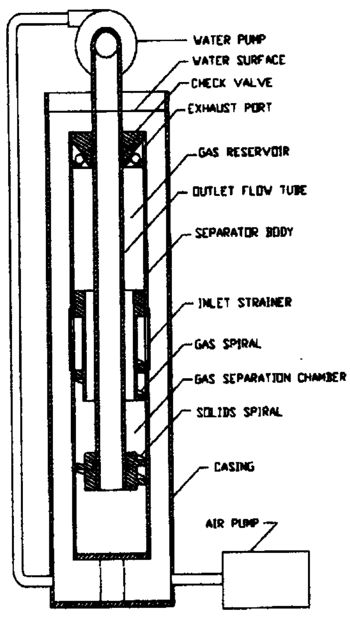

FIGURE 3
LABORATORY TEST SETUP
GAS/LIQUID SEPARATOR

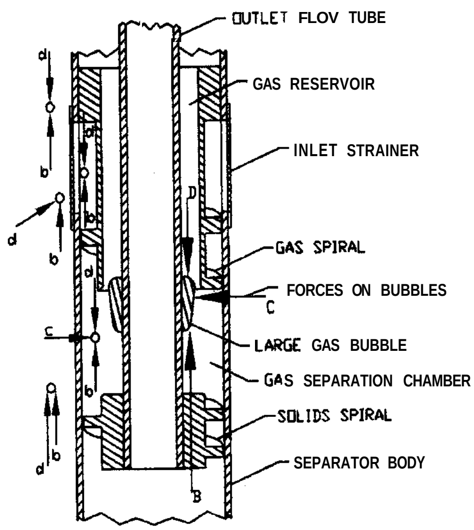

FIGURE 4
GAS-BUBBLE FORCES
IN SEPARATOR