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2004
THE EFFECT OF GEOMETRY ON THE EFFICIENCY OF DOWNHOLE GAS SEPARATORS

by

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The Effect of Geometry on The Efficiency of Downhole Gas Separators

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This work is dedicated to my wonderful and supportive wife, Dianna,

and to my wise and lovely mother, Gladys.
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ABSTRACT

The Effect of Geometry on the Efficiency of Downhole Gas Separators

by

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The production of free gas is the most difficult and most common problem in artificial lift systems such as sucker rod pumps, progressing cavity pumps and electro submersible pumps. A downhole gas separator correctly designed is the most effective way to deal with this problem.

The objective of this project is to study the effect of the geometry on the efficiency of downhole gas separators. In order to study the geometry effect, an apparatus was built that simulates a producing well.

Major modifications were implemented to enhance the experimental facilities at the artificial lift laboratory of the Petroleum and Geosystems Engineering Department at the University of Texas at Austin.

The apparatus built in this laboratory can manage different rates of water and air which can be controlled to evaluate the performance of various separator designs (eleven downhole gas separator models were tested). All the tests were recorded with a digital camcorder to generate video files that were later analyzed and an experimental methodology was developed.
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1. INTRODUCTION

One of the most common problems in artificial lift systems is the production of free gas. Sucker Rod Pumps, Hydraulic Pumps, Progressing Cavity Pumps (PCP) and Electrical Submersible Pumps (ESP) have problems pumping the liquid efficiently in the presence of free gas.

Free gas generates problems such as cavitation, pump off, head reduction, gas blocking, gas locking, slugging. These problems generate reduction of production (pumping efficiencies are severely affected when gas is produced through the downhole pump) and many operational problems.

There are many ways to try to solve this problem such as decreasing the flow rate, lowering the pump, using oversized pumps, changing the pump speed, etc.

Unfortunately, using some of these methods we may see a big reduction of our oil production and/or will increase operating cost.

Therefore, a gas separator correctly designed is probably the most effective way to deal with free gas using a design that does not have moving parts that are worn away and should be relatively economical.

1.1 Effect of free gas on downhole pumps

The volumetric efficiency is defined as the ratio between the actual volume of liquid pumped and the total volumetric capacity of the pump:

\[
E_v = \frac{V_L}{V_P}
\]

1-1

The main factor that produces a reduction of the efficiency of the downhole pump is the presence of free gas. (Campell 1989).

In the case of sucker rod pumps, the volumetric efficiency is affected by three factors such as the slippage of fluid through the plunger-barrel fit, the leakage through the
valves and the presence of free gas in the pump. If the plunger-barrel fit is adequate and the valves operate properly; the reduction of the efficiency due to the slippage and the leakage is very small (Clegg 1963, Schmidt 1986).

Free gas has two negative effects on the sucker rod pump; it occupies a volume destined for handling of liquid and due to the high compressibility of the gas, it produces interference on the operation of the valves (Clegg, 1963). In the case of gas interference, a larger clearance between the standing and the traveling valve reduces even more the efficiency of the system (Dottore 1994).

In the case of progressing cavity pumps, the volumetric efficiency is affected by two factors such as the liquid slippage between the rotor and stator and the volume occupied by free gas in the pump. Under normal condition of operation, the main factor that reduces the efficiency of the pump is the effect of free gas. Also, when the pump handles considerable amounts of free gas, the capacity of the fluid to lubricate the rotor and minimize friction is drastically reduced. The elastomer-stator is very sensitive to high temperatures; this will reduce the life of the pump.

In the case of electrical submersible pumps (ESP), laboratory studies (Lea 1982) show that free gas volumes exceeding 10% of total volume cause serious deterioration in the pump head-capacity curve. If free gas is allowed to enter the pump, it tends to cause the ESP to cycle, resulting in additional pump and motor wear and eventual contamination of the motor oil with wellbore fluids. Entry of free gas through the intake of an electrical submersible pump can cause the pump to shut down on underload.

Since an ESP is not based on positive displacement pumping but on the transfer of momentum to the fluid, the actual flow rate is highly sensitive to the fluid viscosity. Pump underload is due to the reduction of the viscosity, by the presence of the gassy fluid exerting less drag on the impellers (Jacobs, 1983). This is the main cause of underload and results in frequent shutdowns and restarts are known as "cycling". Cycling causes additional wear on the pump and motor, and can lead to contamination of the motor oil with wellbore fluids. Contamination lowers the dielectric strength of the motor oil and could eventually result in motor burn.
1.2 Handling the gas through the casing-tubing annulus

The most common way to handle the free gas is through the casing-tubing annulus. In some cases, we cannot locate the pump below the perforations; the motive of this can be technical or economic. Figure 1-1 shows a schematic of a system where the pump cannot be located below the perforations. The gas flows upward in a static column of liquid in the annular space (casing-tubing). The flowing gas reduces considerably the density of the column of fluid in the annulus, therefore the fluid level could be far above from the theoretical liquid-only column level computed from the bottom flowing pressure and the liquid density. This phenomenon has been studied to solve the problem of determining bottomhole flowing pressure from fluid level measurement (Persen and Podio 1992). At low gas rates, the mixture pressure gradient is correlated with the gas Froude number, which seems to indicate that the flow mechanism is controlled by buoyancy effects. The gas Froude number is expressed by the following relationship:

\[
Fr_g = \frac{v_g}{\sqrt{gD}} \sqrt{\frac{\rho_l}{\rho_l - \rho_g}}
\]

1-2

\( v_g \) is the superficial gas velocity, \( g \) is the acceleration of the gravity and \( D \) is the pipe diameter.

At high gas flow rates, the mixture pressure gradient is correlated with the gas Reynolds number, indicating that the flow is controlled by friction and momentum forces.

In most oil wells there is a mixture of liquid and gas in the annulus above the pump. The top of this fluid mixture column is defined as the “burnout level”; above this level only exists gas. To try to lower the burnout level we have to increase the casing well head pressure. When the gas reaches the pump intake (the burnout level is too low), it can produce a “pumped off” condition, in this case the liquid pumping action stops until enough liquid is accumulated in the annulus to allow the filling of the pump. To try to solve this problem, the pumping speed could be reduced but that would also reduce the
oil production. That is why it is desired to maintain the wellhead casing pressure as low as possible, so that the maximum flow rate is produced. The easiest way to handle the gas at the well head is to connect the casing gas outlet to the flow line. If the tubing well head pressure is low, we will need a special facility such as an independent gas flow line or compressor.

Figure 1-1: Arrangement to handle the gas through the annulus
1.3 Objectives and Scope of this Work

A summary of the objectives sought in each chapter of this project is presented in this section.

1.3.1 Completion of an Extensive Literature Survey (Chapter 2)

The literature survey presented in chapter two presents multiphase flow, two phase flow regimes in pipes or annular flow, holdup behavior, the slip or holdup effect, downhole gas separators and summaries of forty-two patents of downhole gas separator.

The section entitled “Downhole Gas Separators” (2.6) presents descriptions of the working principles of the most common types of separators.

The factors that affect the pressure drop in a vertical pipe associated with either single or multiphase flow are viscosity, surface tension, temperature, pressure and viscous drag. These factors are explained in Appendix A.

The summary of patents will help us in the design and analysis of the downhole separator test system. These patents are divided into two groups: Centrifugal Gas-Separators and Gravity gas separators (Appendix C).

1.3.2 Experimental Facilities (Chapter 3)

The tests were conducted at the laboratory of the Petroleum and Geosystems Engineering Department at The University of Texas at Austin.

An apparatus that simulates a producing well was built in which different rates of water and air can be controlled to evaluate the performance of various separator designs.

Manual valves and flow indicators constituted all the control and measurement system of the experimental loop.

All the tests were recorded with a digital camcorder to generate video files of the flow behavior in the separators that were later analyzed.
1.3.3 Experimental Procedure (Chapter 4)

The acquisition of relevant data such as gas rate injected into the well, volume of the gas injected into the well, liquid rate injected into the well, casing pressure, ports pressure, separator exit pressure, and gas rate flowing through gas separator is the basis for the analysis of the behavior of the different downhole gas separators models studied in this project. The data generated in each test were saved in an Excel file and, with this data, graphs were generated to analyze the behavior of the downhole gas separator being tested.

The experiment simulates an oil well producing with gas interference. Since the experiment is carried out in an indoor laboratory the fluids used are water simulating the liquid (oil and water) and air simulating the gas. A downhole gas separator is placed inside the wellbore and a group of tests for each casing pressure (5 and 10 psi), each separator model (Patterson’s and Echometer’s models) and each position of the downhole gas separator (in front, under and above the perforations) are performed. Water is injected at different rates, from 100 to 700 BBD, depending on the requirements of the experiments, with rates of air mixed with water injected, from 10 up to 118.70 MSCFD.

1.3.4 Discussion of Experimental Results (Chapter 5)

Eleven downhole gas separator models were tested; these are Patterson’s models (7), Echometer’s models (3) and Bucket model (1). These models are mechanical models constructed in the Lab.

In this chapter the performance of each separator is studied and the test data spreadsheet is included. The data saved in the spreadsheet is used for graph and analyzed the behavior of each separator model. Because, it has to be errors in the measurements of our variables, it is included a pictures of each point data to help for visual observations.

Other considerations and visual observations found in the conductions of the tests are explained in this chapter 5.5.
2. LITERATURE SURVEY

2.1 Multiphase Flow

The simultaneous flow of two or more phases of fluid is called multiphase flow. This phenomenon occurs in almost all oil production wells, in many gas production wells and in some types of injection wells. In oil production wells, when the pressure drops below the bubble point, gas will be liberated; therefore we will have a gas-liquid flowing from that point to the surface. Many oil wells also produce amounts of water, resulting in oil-water flow or in oil-water-gas flow.

2.1.1 Fundamental Concepts

The application of fundamental equations to the flow of multiphase mixtures is complicated by a number of factors which are not present in the case of single-phase systems (Govier and Aziz 1987). These factors are the followings:

- The flow of the multiphase mixtures may not be characterized as merely laminar or turbulent flow, but the relative fluid quantities and the distribution of the phases must be considered.
- The presence of the interface between the phases itself adds to the complexity of the problem, and the fundamental equations must be written for the interface as well as for the individual phases.
- The energy associated with the creation of the surface must be considered in the total energy equation when a large amount of interfacial surface is involved.
- The separate phases move at different average velocities and the in situ concentrations are not the same as the ratio of the flow rates. The variation of the in situ concentrations from the flow rate ratio is referred to as the holdup phenomenon.

Appendix A explains in detail the fundamental equations describing the flow of multiphase mixtures.
2.2 Two-Phase Flow Regimes in Pipe or Annular Flow

The flow regime or flow pattern is a qualitative description of the phase distribution. The distribution of the two phases in the pipe affects other aspects of two-phase flow, such as slippage between phases and the pressure gradient.

Multiphase flow (Figure 2-1) may be categorized into four different flow configurations or flow regimes, consisting of bubble flow, slug flow, slug-mist transition flow and mist flow (Caetano, 1992). These occur as a progression with increasing gas rate for a given liquid rate.

**Figure 2-1: Flow pattern (From Schlumberger oilfield glossary)**

- **Bubble flow**: Continuous liquid phase with evenly dispersed gas bubbles
- **Slug flow**: Continuous liquid phase with irregular gas bubbles
- **Transition flow**: Interrupted liquid phase with chaotic gas distribution
- **Mist flow**: Continuous gas phase with liquid entrained as mist and an annular film on tubing wall
**Bubble Flow**

There are dispersed bubbles of gas in a continuous liquid phase. In bubble flow, the liquid is continuous with the gas phase existing as bubbles randomly distributed. The gas phase in bubble flow is small and contributes little to the pressure gradient except by its effect on the density. A typical example of bubble flow is the liberation of solution gas from an undersaturated oil at and above the point in the flow string where its bubble point pressure is reached.

**Slug Flow**

Slug flow accounts for a large percentage of two-phase flow in production wells and, as a result, a good deal of research has been concentrated on this flow regime. In slug flow, both the gas and liquid phases significantly contribute to the pressure gradient. At higher gas rates, the bubbles coalesce into larger bubbles, called Taylor bubbles that eventually fill the entire flow cross section. Between the large gas bubbles are slugs of liquid that contain smaller bubbles of gas entrained in the liquid.

In circular pipes the gas bubbles are rounded on their leading edge, fairly flat on their trailing edge and are surrounded on their sides by a thin liquid film. Liquid entrainment in the gas phase occurs at high flow velocities and small gas bubbles occur in the liquid slug. The velocity of the gas bubbles is greater than that of the liquid slugs, thereby resulting in a liquid holdup that not only affects friction losses but also flowing density.

**Churn or Transition Flow**

In transition flow, the liquid slugs between the gas bubbles essentially disappear, and at some point the liquid phase becomes discontinuous and the gas phase becomes continuous. With a further increase in gas rate, the larger gas bubbles become unstable and collapse, resulting in churn flow, a highly turbulent flow pattern with both phases dispersed. The pressure losses in transition flow are partly a result of the liquid phase, but are more the result of the gas phase. Churn flow is characterized by oscillatory, up-and-down motions of the liquid.
Annular or Mist Flow

At higher gas rates, gas becomes the continuous phase, with liquid flowing in an annulus coating the surface of the pipe and with droplets entrained in the gas phase. Mist flow is characterized by a continuous gas phase with liquid occurring as entrained droplets in the gas stream and as a liquid film wetting the pipe wall. A typical example of mist flow is the flow of gas and condensate in a gas condensate well.

2.2.1 Two-Phase flow in vertical pipes

The parameters used to describe single-phase flow are not enough to describe two-phase flow. Visual observation of the phenomenon shows the existence of several different and well-defined macroscopic behaviors or morphological arrangements of the flow for different combinations of the phases flow rates. Based on those morphological arrangements, there were defined different flow patterns. These flow patterns are used for interpretation and prediction of the pressure drop and other physical quantities involved in the phenomenon.

There are many flow pattern maps of various kinds. Galegar, Stovall and Huntington (1954), Kozlov (1954), Govier and Aziz et al. (1957, 1961) and others have all made a different flow pattern maps.

These maps propose flow pattern transition boundaries in a two-dimensional coordinate system as determined from experiments.

Duns and Ros (1963) defined a plot that relates flow regime to flow rates of each phase, fluid properties, and pipe size. One such map that is used for flow regime discrimination in some pressure drop correlations is that of Duns and Ros (1963), shown in Fig. 2-2. The Duns and Ros map correlates flow regime with two dimensionless numbers, the liquid and gas velocity numbers, \( N_{vl} \) and \( N_{vg} \), defined as:

\[
N_{vl} = u_{vl} \times \frac{\rho_l}{\sqrt{g \sigma}}
\]
\[ N_{vg} = u_{vg} \times \sqrt[4]{\frac{\rho_1}{g\sigma}} \]

\( \rho_1 \) is liquid density, \( g \) is the acceleration gravity and \( \sigma \) is the interfacial tension of the liquid-gas system. This flow pattern map does account for other fluid properties; note, however, that for a given gas-liquid system, the only variables in the dimensionless groups are the superficial velocities of the phases.

Duns and Ros defined three distinct regions on their map, but also included a transition region where the flow changes from a liquid continuous to a gas continuous system. Region I contains bubble and low-velocity slug flow, Region II is high-velocity slug and churn flow, and Region III contains the annular flow pattern.

**Figure 2-2: Duns and Ros regime map (From Duns and Ros, 1963)**
In 1961, Griffith and Wallis presented theoretical support for the dimensionless groups, at least to describe the transition from the slug to annular flow patterns. Taitel, Barnea and Dukler (1976 and 1980) presented a mechanistic discussion to predict the conditions under which transition between flow patterns would take place. This map is based on a theoretical analysis of the flow regime transitions. This map must be generated for particular gas and liquid properties and for a particular pipe size; a Taitel-Dukler map for air-water flowing in a 2 inch-ID pipe is shown in Figure 2-3.

This map identifies five possible flow regimes: bubble, dispersed bubble (a bubble regime in which the bubbles are small enough that no slippage occurs), slug, churn and annular. The slug/churn transition is significantly different than that of other flow regime maps in that churn flow is thought to be an entry phenomenon leading to slug flow in the Taitel-Ducker theory. The D lines show how many pipe diameters from the pipe entrance churn flow is expected to occur before slug flow develops. For example, if the flow conditions falls on the D line labeled Le/D=100, for a distance of 100 pipe diameters from the pipe entrance, churn flow is predicted to occur; beyond this distance slug flow is the predicted flow regime.

**Figure 2-3: Taitel-Ducker flow regime map (From Taitel et al., 1976)**
2.2.2 Two-phase flow in vertical annuli

An annulus is the space between two concentric objects, such as between the wellbore and casing or between casing and tubing, where fluid can flow. The pipes may consist of drill collars, drill pipe, casing or tubing. In production, the annulus is the space between the casing and the tubing therefore the flow occurs through the area bounded by the outer pipe inner wall (casing) and the inner pipe outer wall (tubing).

**Figure 2-4: Annulus space (From Schlumberger Oil Field Glossary)**

**Annulus pipe diameter ratio:** It is the ratio between the outer diameter of the inner pipe (tubing) and the inner diameter of the outer pipe (casing):
\[ K = \frac{D_T}{D_C} \]

\( D_T \) is the outer diameter of the inner pipe and \( D_C \) is the inner diameter of the outer pipe.

**Eccentricity:** In mathematics, eccentricity is a parameter associated with every conic section. It can be thought of as a measure of how much the conic section deviates from being circular. For example, the eccentricity of a circle is zero, the eccentricity of an ellipse is greater than zero and smaller than 1, the eccentricity of a parabola is 1, the eccentricity of a hyperbola is greater than 1 and the eccentricity of a straight line is infinity.

**Conic Section:** A family of curves to which the circle, ellipse, parabola, and hyperbola belong. It includes all the possible paths of a point that moves so that its distance from a fixed point (the focus) is a constant fraction of its distance from a fixed line (the directrix). This fraction is known as the eccentricity. Conic sections are so named because they can be obtained by slicing through a right circular cone at various different angles.

**Figure 2-5: Conic sections (from Wikipedia)**
Effect of Eccentricity

Haciislamoglu, Nakagawa and Bourgoyne made some visual studies of multiphase flow in clear tubes. These studies showed that large gas bubbles normally exist in gaseous liquid columns. The liquid rest in the annulus but the gas flows through the liquid column and is produced at the surface.

When the tubing is concentric with the casing, the gas distribution will be uniform throughout the annular area. When the tubing is eccentric with the casing, gas will flow preferentially in the larger side of the annulus. Therefore, liquid concentration will be higher in the narrow portion where the two tubes are almost touching. A continuous circulation of fluid takes place with liquid being incorporated from the narrow side into the high-velocity wide side, then carried upwards some distance and then as the gas slips through, the liquid is discarded back to the narrow side. The liquid near the narrow side of the annulus then moves downwards under its own hydrostatic and eventually is re-entrained into the wide side of the annulus.

Degree of eccentricity: It is the displacement of the inner pipe center from the outer pipe center and is expressed as

\[ e = 2 \times \frac{DBC}{(D_c - D_f)} \]

Where, DBC is the distance between the pipes centers. Annuli can have eccentricity values varying from zero to one. Figure 2-6 shows sections of annuli with the same pipe diameter ratio value, K and for eccentricities of 0.0, 0.5, and 1.0.
For single-phase flow of fluids, annuli have been treated based on the hydraulic diameter concept. The hydraulic diameter is four times the area for flow divided by the wetted perimeter. Caetano et al. (1992) made a experimental investigation in concentric and fully eccentric annuli using air-water and air-kerosene mixtures. Caetano concluded that the hydraulic diameter is only appropriate for high degrees of turbulence. Using the hydraulic diameter predicting friction factor values in annular configurations can have errors that can vary between -40 to 50 percent, depending on the pipe diameter ratio and the degree of eccentricity.

2.2.3 Flow Pattern Transition Prediction

Caetano (1992) used the Taitel model (1980) to predict the flow pattern transition boundaries in a concentric annulus. The annulus characteristic dimension was represented by the hydraulic diameter and its equivalent diameter (a diameter for a pipe which has the same cross-sectional area as the actual annulus). Neither concept when applied to the Taitel flow pattern transition model performed satisfactorily. The main weaknesses were in the prediction of the bubble to slug flow pattern transition at low liquid flow rates, the transition to dispersed bubble flow and prediction of the existence of the bubble flow
region. Caetano developed the modified model that was made from modifications of the Taitel flow pattern transition model.

**Bubble Flow Region**

The different characteristic velocities of the small bubble and the Taylor bubble can determinate the existence of bubble flow is determined. The velocity of the discrete bubble only depends of the phase physical properties. This is independent of pipe diameter but the Taylor bubble rise velocity, for inertia-dominated conditions, does depend on the pipe diameter. At any time that the discrete bubble rise velocity is larger than the Taylor bubble rise velocity, the discrete bubbles approach the back of the Taylor bubble and coalescence takes place (Taitel). When this occurs, bubble flow cannot exist.

The occasionally occurring Taylor bubble rises through an array of discrete bubbles when the Taylor bubble rises through an array of discrete bubbles. Coalescence does not take place as the discrete bubbles are swept around the front of the Taylor bubble. In this way, the Taylor bubble will disappear from the pipe, allowing the existence of the bubble flow pattern. The discrete bubble rise velocity depends only on the physical properties of the phases and is given by:

$$V_{0, \infty} = 1.53 \left[ \frac{(\rho_L - \rho_G)g\sigma}{\rho_L^2} \right]^{1/4}$$

2-38

This equation was found by Harmathy (1955) who used in his work bubbles for which the Reynolds number is greater than 500. In this region the viscous effects are negligible.

The Taylor bubble rise velocity for inertia-dominated conditions in an annulus can be predicted by:

$$V_{TB} = 0.345 \sqrt{gD_{EP}}$$

2-39
D_{EP} is the equi-periphery diameter, \((D_{EP}=D_C+D_T)\). Bubble flow can exist if \(V_{TB}>V_{0\infty}\). The bubble flow pattern region in annuli exists when:

\[
D_{EP} \geq 19.7 \sqrt{\frac{(\rho_L-\rho_G)g\sigma}{\rho_L^2}}
\]

**Bubble to Slug Transition**

The bubble to slug flow pattern transition is controlled by an agglomeration mechanism at low superficial liquid velocities. The gas phase is distributed into discrete bubbles when the gas is introduced at low flow rates, the turbulence is negligible. These bubbles move upward in a zigzag path with considerable randomness, occasionally forming large bubbles. As increasing the gas rate, the bubble size and number increase. The transition to the slug flow pattern is caused by an increase in rate of collision which increases the rate of agglomeration. This point is reached where the bubbles become closely packed.

For uniformly distributed bubbles, the transition occurs when the gas void fraction reaches 0.25 (Taitel). For flow through the concentric annulus, an average gas void fraction value of 0.20 was measured at the bubble to slug transition boundary. For flow through the fully eccentric annulus, a still lower gas void fraction value of 0.15 was measured at the bubble to slug transition boundary. This lower value is due to the pressure of cap bubbles and to the higher local gas fraction in the widest region of the eccentric annulus case. Thus, the Taitel et al. model is modified for the bubble to slug transition in an annulus by using values of the gas void fraction measured at this transition. The in-situ gas and liquid velocities are related by:

\[
\frac{V_{SG}}{H_{SG}} = \frac{V_{SL}}{H_{SL}} + V_{0\infty}
\]
Substituting Equation 2-38 in equation 2-41, and using the measured void fractions for the annular configuration yield:

\[ V_{SG} = \frac{V_{SL}}{0.4} + 0.306\left[ \frac{(\rho_L - \rho_G)g\sigma}{\rho_L^2} \right]^{1/4} \]  
\[ \text{2-42} \]

\[ V_{SG} = \frac{V_{SL}}{5.67} + 0.230\left[ \frac{(\rho_L - \rho_G)g\sigma}{\rho_L^2} \right]^{1/4} \]  
\[ \text{2-43} \]

For the bubble to slug transition boundary at low liquid flow rates, in the concentric and fully eccentric annuli, respectively.

**Bubble or Slug to Dispersal Bubble Flow Transition**

Gas phase in either slug or bubble flow patterns break into small bubbles and become dispersed in the continuous liquid phase. This is caused by turbulence forces due at high superficial liquid velocities (Taitel).

Dispersed bubble flow occurs when the turbulent fluctuation intensity is sufficiently high to break the Taylor bubbles into fine bubbles smaller than a critical size to prevent reagglomeration. The expression for the bubble or slug to dispersed bubble flow transition using the hydraulic diameter concept is expressed as:

\[ 2\left[ \frac{0.4\sigma}{\rho_L - \rho_G g} \right]^{1/2} \left[ \frac{\rho_L}{\sigma} \right]^{3/5} \left[ \frac{2}{D_H} \right]^{2/5} f_{XA}^{2/5} V_{M}^{6/5} = 0.725 + 4.15 \left[ \frac{V_{SG}}{V_M} \right]^{1/2} \]  
\[ \text{2-44} \]

where \( V_M \) is the mixture superficial velocity and \( f_{XA} \) is the Fanning friction factor (one fourth of the friction factor from the Moody diagram) evaluated for the homogeneous mixture and takes the value of \( f_{CA} \) or \( f_{EA} \) in the cases of concentric or eccentric annulus respectively. The values of \( f_{CA} \) and \( f_{EA} \) are given by the equation for turbulent regime, for laminar zone the Fanning friction factors are given by: \( f_{XA} = f_{CA}/\text{Re} \).
\[
\left\{ f_{\lambda d} \left[ \frac{16}{F_{XA}} \right] \right\}^{0.45 \exp \left[ 10^{-6} \left( \text{Re} - 3000 \right) \right]} - 1^{1/2} = 4 \log \left\{ \text{Re} \left[ f_{\lambda d} \left[ \frac{16}{F_{XA}} \right] \right] \right\}^{0.45 \exp \left[ 10^{-6} \left( \text{Re} - 3000 \right) \right]} - 0.4
\]

2-45

\( F_{XA} \) is the friction geometry parameter that becomes \( F_{CA} \) for the case of concentric:

\[
F_{CA} = \frac{16(1 - K)^2}{1 + K^2 + \frac{1 - K^2}{\ln K}}
\]

2-46

For the case of eccentric annuli, \( F_{XA} \) is the friction geometry parameter that becomes \( F_{EA} \)

\[
F_{EA} = \frac{(1 - K)^2 (1 - K^2)}{\text{Re} \, \phi \, \sinh^4 \eta_0}
\]

2-47

\[
\cosh \eta_i = \frac{K(1 + e^2) + (1 - e^2)}{2Ke}
\]

2-48

\[
\cosh \eta_0 = \frac{K(1 - e^2) + (1 + e^2)}{2e}
\]

2-49

\[
\phi = (\cosh \eta_i - \cosh \eta_0)^2 \left[ \frac{1}{\eta_0 - \eta_i} - 2 \sum_{n=1}^{\infty} \frac{2n}{\exp(2n \eta_i) - \exp(2n \eta_0)} \right] + \frac{1}{4} \left( \frac{1}{\sinh^4 \eta_0} - \frac{1}{\sinh^4 \eta_i} \right)
\]

2-50

Equation 2-45 is implicit with respect to \( f_{\lambda A} \), which makes it difficult to apply in calculations. The following methodology overcomes this problem. An intermediate variable \( y \) was defined as:
\[ y = \left\{ f_{Xd} \left[ \frac{16}{F_{Xd}} \right]^{0.45 \exp \left[ 10^4 (Re-3000) \right]} \right\}^{1/2} \]

2-51

Therefore equation 2-45 can be rearranged as:

\[ y = \frac{1}{4 \log(yRe) - 0.4} \]

2-52

It was found that the following expression gives accuracy better than 2% in the range of Reynolds number from 15 to 50,000

\[ y = 0.4643 [\log Re]^{-1.195} \]

2-53

The last equation can be used for fast calculations or as a first guess when equation 2-52 is used with an iterative algorithm. After obtaining the value of \( y \) the friction factor is given by:

\[ f_{Xd} = y^2 \left[ \frac{F_{Xd}}{16} \right]^{0.45 \exp \left[ 10^4 (3000 - Re) \right]} \]

2-54

For a uniform bubble size distribution and a cubic lattice packing, the maximum allowable gas void fraction for dispersed bubble conditions is 0.52. Higher values of void fraction will cause transition to slug flow. Using this criterion and equations 2-38 and 2-41 yield the following transition boundary to dispersed bubble flow for gas void fractions above 0.52

\[ V_{SG} = 1.083 V_{SL} + 0.7960 \left[ \frac{(\rho_L - \rho_g) g \sigma}{\rho_L^2} \right]^{1/4} \]

2-55
**Transition to Annular Flow**

The mechanism that cause the transition to annular flow (for pipe flow) is related to the minimum gas velocity necessary to transport upward the largest liquid droplet entrained in the gas core (Taitel). The liquid droplets would fall back, accumulate, from a bridge and churn or slug flow would prevail for lower gas velocities.

Making a balance between drag and gravity forces acting on the largest stable droplet, we can determine the required minimum gas velocity. If we neglect the effect of the film thickness, the transition is given by

\[
V_{sg} \geq 3.1 \left[ \frac{(\rho_L - \rho_G)g \sigma}{\rho_G^2} \right]^{1/4}
\]

[2-56]

The geometry of downhole gas separator in vertical or inclined annuli involves two-phase flow. This phenomenon takes place in the annulus between the casing and the separator as well as in the annular geometries formed by the internal components of the separator. The determination of the flow pattern at the separator entrance and inside the separator is important because of its effect on the pressure drop through the separator and because of the effect of the turbulence on the separation process.

**2.3 Counterflow**

In the last section was discussed multiphase flow when the two fluids are flowing in the same direction. Inside the separator, the gas that was not liberated to surface and the liquid flow together in the same direction in the dip tube, but in the annular space between the dip tube and the separator outer tube, there are two different phenomena:

1. The liquid with some gas entrained by the liquid are flowing down and into to the dip tube.
2. Large gas bubbles are going up escaping to the well annulus through the separator ports.

Therefore some fluid is going down to the dip tube and another fluid is going up to surface, this is well known as counterflow (figure 2-7).

![Figure 2-7: Counterflow](image)
2.4 Holdup Behavior

Liquid holdup is defined as the in-situ flowing volume fraction of liquid. In two phase flow, the amount of the pipe occupied by a given phase is often different from its proportion of the total volumetric flow rate. Figure 2-8 shows an example of a typical two-phase flow situation, consider the upward flow of two phases, α and β, where α is less dense than β. Typically, in upward two-phase flow, the lighter phase (α) will be moving faster than the denser phase (β). Because of this fact, called the holdup phenomenon, the in-situ volume fraction of the denser phase will be greater than the input volume fraction of the denser phase – that is, the denser phase is “held up” in the pipe relative to the lighter phase. Correlations for holdup are generally used in two-phase pressure gradient calculations.

Figure 2-8: Schematic of two-phase flow
The phenomenon called holdup, $y$, is defined as:

$$y_\beta = \frac{V_\beta}{V}$$  \hspace{1cm} 2-57

$$y_\alpha = \frac{V_\alpha}{V}$$  \hspace{1cm} 2-58

Where $V_\beta$ is the volume of the denser phase in the pipe segment, $V_\alpha$ is the volume of the higher phase and $V$ is the volume of the pipe segment. Because the pipe is completely occupied by two phases:

$$y_\alpha = 1 - y_\beta$$  \hspace{1cm} 2-59

The holdup, $y_\beta$, or $y_\alpha$ can also be defined in terms of a local holdup, $y_{\beta 1}$ or $y_{\alpha 1}$ respectively, as:

$$y_\beta = \int\limits_0^A \frac{y_{\beta 1}}{A} dA$$  \hspace{1cm} 2-60

The local holdup, $y_{\beta 1}$ or $y_{\alpha 1}$, is a time-averaged quantity – that is, $y_{\beta 1}$ or $y_{\alpha 1}$ is the fraction of the time a given location in the pipe is occupied by phase $\beta$ or $\alpha$. In gas-liquid flow, the holdup of the gas phase, $y_\alpha$, is sometimes called void fraction.

**Input Fraction ($\lambda$):** Another type of parameter used in describing two-phase flow is the input fraction. This factor is calculated for each phase, defined as
\[ \lambda_\beta = \frac{q_\beta}{q_\alpha + q_\beta} \]

2-61

\[ \lambda_\alpha = 1 - \lambda_\beta \]

2-62

Where \( q_\alpha \) and \( q_\beta \) are the volumetric flow rates of the phases \( \alpha \) and \( \beta \), respectively. The input volume fractions, \( \lambda_\alpha \) and \( \lambda_\beta \), are also referred to as the “no-slip holdups”.

**Slip Velocity (\( u_s \))**: Slip velocity is defined as the difference between the average velocities of the two phases. The slip velocity is defined as:

\[ u_s = \bar{u}_\alpha - \bar{u}_\beta \]

2-63

where \( \bar{u}_\alpha \) and \( \bar{u}_\beta \) are the average in-situ velocities of the two phases. Slip velocity is not an independent property from holdup, but is simply another way to represent the holdup phenomenon.

**Superficial Velocity**: It is the relationship between holdup and slip velocity. The superficial velocity of a phase is the average velocity of the phase if that phase filled the entire pipe; that is, if it were single-phase flow. In two-phase flow, the superficial velocity is not a real velocity that physically occurs, but simply a convenient parameter. The superficial velocity is defined as:

\[ u_{sa} = \frac{q_\alpha}{A} \]

2-64
\[ u_{s\beta} = \frac{q_{\beta}}{A} \]

The average in-situ velocities, \( \bar{u}_\alpha \) and \( \bar{u}_\beta \) are related to the superficial velocities and the holdup by

\[ \bar{u}_\alpha = \frac{u_{s\alpha}}{y_{\alpha}} \]

\[ \bar{u}_\beta = \frac{u_{s\beta}}{y_{\beta}} \]

2.5 Downhole Gas Separators

A downhole gas separator is a device that separates free gas from the fluid in the wellbore. Its function is to separate as much of the free gas as possible, so that the free gas is handled naturally through the tubing-casing annulus and not by the pump.

There are several terms that have slightly different definitions for different researches, therefore we will use the following terminology presented by McCoy at al, 1995:

**Gas Separator:** The complete assembly of elements installed bellows the pump with the purpose of maximizing the amount of liquid entering the pump.

**Outer Barrel:** This is the outer element of the separator which is connected to the tubing. Sometimes it is called mud anchor.

**Dip Tube:** This is the innermost element of the gas separator which is attached to the pump intake. Often this is called suction tube and sometimes gas anchor.
Many gas separators have been devised that use various physical mechanisms to obtain separation. Among these are gravity, agitation and centrifugal force. The basic premise of gas separation focuses on gas and fluid velocities in the wellbore and downhole production equipment.

Free gas may flow simultaneously with the liquid from the reservoir rock or may evolve from the oil due to pressure reduction. When oil containing solution gas crosses the perforations or anchor ports in a mud anchor, a pressure drop is observed resulting in the evolution of free gas bubbles. In addition, agitation, change in direction, and sudden velocity increases result in the evolution of free gas. Depending on the size and shape of the bubbles, fluid viscosity and velocity, the free gas bubbles will attempt to migrate upward while the fluid moves downward. If the downward fluid velocity exceeds the critical velocity required for upward migration of the gas bubbles, free gas will be forced through the production equipment. Therefore, successful gas separation may be achieved by employing gas separators that ensure downward fluid velocities which do not exceed the aforementioned critical velocities.

There are many parameters that influence in the efficiency of the downhole gas separator but the most impotents are viscosity of the oil, temperature, pressure and liquid and gas surface velocities.

**Types of Downhole Gas Separators**

Through the years many different types of gas separators have been developed and utilized in pumping applications with varying degrees of success. The literature survey in chapter 2, summarizes various patents of separators issued since 1956 until today. The downhole gas separators depend on the density contrast between the fluids (liquid and gas). However, gravity, centrifugal forces or a combination of both have been used as driving forces in the separation process. The Downhole Gas Separators are divided in the following types:
Gravity Driven Static Separators

Gravity driven gas separators take advantage of phenomenon of flotation of the gas bubbles. When we have a stationary liquid-gas mixture, the tendency of the gas bubbles to float in the liquid provides a natural separation process. Therefore these kinds of downhole separators have a special geometry that favors the rising movement of the gas in the liquid.

The rising velocity of the bubbles depends on the shape and size of the bubbles, and on the viscosity, density and surface tension of the liquids (Peebles et al., 1953 and Harmathy et al., 1960).

A good summary of the most common gravity driven gas separators is presented by Clegg (1989). The components those gas separators are an inlet port or ports, a downward flow zone, a port or ports and a dip tube or chamber.

The inlet port or ports is where part of the gas is separated and the liquid-gas mixture enters the gas separator. If the rising velocity of the bubbles relative to the liquid is greater than the liquid velocity, separation will be achieved in the downward flow zone, otherwise, the gas will be dragged with the liquid and the performance of the separator will be poor. The separation of the gas is realized in the port or ports. The dip tube or chamber drives the fluid from the lower zone of the gas separator to the pump inlet.

Figure 2-9 shows a gravity driven gas separator. There are many different designs in this kind of separators such as the simplest concentric tubing (poorboy) or the most complicated geometric arrangements (wormcup).
Static Centrifugal Separators

This kind of separators use the inertial forces produced by the circular motion of the fluid inside the gas separator. In the static separators, helical vanes induce a rotational velocity on the mixture flow. As the density of the liquid is greater than the gas density, the liquid tends to move to the outer zone of the chamber, while the gas tends to stay in the inner zone. A cross over is required to take the liquid from the outer zone to the pump inlet and to take the gas from the inner zone to the tubing-casing annulus. Figure 2-10 show a patented model of the static centrifugal separators.
Decentralized Static Separators

The idea before the sixties is that the separation process occurs mainly inside the separator. But in the early sixties, a good field practice based in the experience, it was to avoid the concentricity of the downhole gas separator with the casing to improve the separation efficiency. In 1992 visual studies of air-water and air-kerosene two-phase vertical flow in transparent tubes showed that in the presence of an eccentric tubing casing arrangement, gas will flow preferentially through the larger side of the eccentric annulus (Caetano et al., 1992).
Due to this new concept of the separation of the gas in the annular space, a new decentralized downhole gas separator was developed based on this phenomenon and presented by McCoy et al., (1995). Figure 2-11 shows this separator.

**Figure 2-11: Decentralized downhole gas separator**

*(From McCoy, J.N., et al., 1995)*

---

**Dynamic Centrifugal Separators**

The high sensitivity of the ESP performance to even a low concentration of gas requires the use of efficient dynamic separators. Gas separators are used to separate the free gas from the fluid before it enters the pump and causes flow cycling.

Dynamic gas separators impart energy to the fluid in order to get the gas to separate from the liquid. The original gas separator was called a KGS (Kinetic Gas Separator or Kobylinski Gas Separator). This design uses an inducer to increase the pressure of the fluid and a centrifuge to separate the vapor and liquid.
This design could be called a centrifugal gas separator. The basic components of this centrifugal gas separator are the intake, inducer, flow divider, crossover, and discharge (Figure 2-12).

The gas/liquid mixture enters through the intake. At this point the gas is distributed evenly throughout the liquid. The mixture then moves on to the inducer. The inducer consists of three sections. The first section is a screw-type inducer that raises the fluid pressure and pumps it through the unit. As the fluid moves through this section, the gas begins to move inward toward the shaft. The fluid then moves through the transition section of the inducer. This section is designed to direct the fluid to the third inducer section, the centrifuge, with a minimum of losses. The centrifuge imparts additional circular motion to the fluid. The principal separation occurs here. The liquid portion of the fluid, being substantially denser, is forced centrifugally to the outside while the lighter gas is displaced toward the center.

The stratified fluid then moves into the flow-divider section. Here the gas and the liquid portions are separated physically. The final section is the crossover and discharge areas, where the liquid is directed inward to tie into the pump stage and the gas is turned outward and vented into the casing annulus.

The equipments used for ESP are the Reverse Flow Separators and the centrifugal Separators (Lea 1982). The reverse flow separator will handle up to 10% free gas, while the rotary gas separator will handle considerably more, with the actual amount depending on wellbore conditions.

The reverse flow separator depends on flotation and surface tension effects and a sharp flow reversal to accomplish free gas separation. It also has an upturned impeller that produces some head and assists in allowing the pump to recharge itself with liquid if it becomes gas-locked.

Original gas separator designs were based on increasing gas separation by forcing the fluid flow to reverse in the wellbore. This is where the name of this type of gas separator, REVERSE FLOW, comes from. The reverse flow gas separator is a modified gas anchor that permits placing the pump intake above the casing perforations by locating
the housing intake ports above inner intake passages. This causes the flow to make a 180° turn, which causes free gas separation to occur. A low downward flow velocity also may permit some additional natural separation. This type of separator has been used in centrifugal pumping applications for fifty years, but its efficiency is limited in applications where moderate to high flow rates are encountered.

A centrifugal separator achieves separation of gas and liquid by the use of cyclone and vortex technology. One of the characteristics of the method is that the separated liquid is concentrated in the vicinity of the wall of the separator while the gas phase concentrates at the center of the system.

The dimensioning of the separator should be based on the equation of the trajectory of the gas bubbles, but an equation that would be general and would also cover the turbulence arising in the process is not available. The usual theoretical approximation is to write the equation of motion by describing the resistance of the medium to liquid and gas by Stokes’ equation for laminar flow. The different velocities of the liquid and gas phases result in severe complications of any theoretical analysis.

The centrifugal gas separator, as shown in the Figure 2-12, consists of an inducer and a high-capacity, highly mixed-flow pump, followed by a separator chamber. The inducer and pump stage are incorporated to provide some means to overcome the resistance of the internal flow and vent passages. The separator chamber consists of the rotating unit with radial vanes and an integral outer shell. The rotating outer shell provides a closed radial chamber where turbulence is minimized because the fluid rotates with the chamber as a solid body (forced vortex). The cross-sectional area is maximized to reduce the axial velocity of the fluid and thereby to maximize its residence time in the chamber, where it is affected by large centrifugal acceleration forces. Due to its higher density, the liquid accumulates near the outer wall and the gas accumulates near the shaft. These fluids are separated into the top of the separator chamber where the liquid is ducted to the first pump stage and the gas is vented to the casing annulus by means of a crossover diffuser.
Natural Gas Separator

The oldest and simplest bottomhole gas separator is the natural gas anchor. The natural gas anchor uses the well as a separator by simply setting the pump intake below the casing perforations (Fig. 2-14).

As the oil and entrained gas bubbles flow through the casing and experience a pressure drop, the bubbles grow in size and begin to rise. As they join other bubbles, they grow even larger. The rate of bubble rise increases with bubble size, with larger bubbles rising at about 0.5 ft/sec [0.15 m/s]. Gravity separation occurs when the fluid downhole velocity is lower than the bubble rise velocity. This is accomplished by maximizing the downflow area. This area is limited by casing size, equipment diameter, and fluid viscosity. If wellbore conditions permit, it is better to use a natural gas separator.
Parallel Type Forced Flow Separator

The forced flow type is one of the most effective downhole gas separators. One design provides a small string of macaroni, strapped parallel to the tubing string. The ends of both strings are threaded into a crossover fitting (Figure 2-14), which diverts all fluids from below a packer cup up through the fitting and macaroni string, where it discharges to the casing annulus.

Separation is generated by dropping the liquids by gravity, to the top of the packer where intake ports feed the dead oil to the pump. This design lacks proper capacity and no provisions are made to baffle the fluids.
Figure 2-14: Forced flow oil & gas separator parallel type
Concentric Type Forced Flow Separator

This type of separator incorporates a fitting with multiple ports carrying the fluids up above a packer cup on the outside of the tubing string. Inside is an annulus formed by one joint of standard line pipe to extend the point of discharge to the casing annulus, which is used as a storage zone to accommodate the dead oil dropping back to the intake ports above the packer. Tubing couplings and short nipples can be used about four feet apart above the separator to the top of the line pipe. Thesecouplings form an annular restriction as the gas/oil flows through these spaces at high velocities.

The space between the couplings forms a larger annulus and the liquid can expand at these points.

Because the fluid alternates at high velocities, then blasts into expansion chambers, a natural baffling is created without going to the expense of a very intricately designed mechanism. After discharging the fluids at the top of the line pipe in the casing annulus, the free gas goes up and the dead oil is dropped into the storage zone above the packer, where multiple intake ports carry it into the pump. The large sizing of the multiple discharge and intake ports in the fitting is important, because it permits greater capacities, to accommodate high gas/oil ratio wells.

The separator of type forced flow also allows a well to make intermittent gas heads without unseating the pump or blowing the packing out of the stuffing box. Some wells that have recently gone from the flowing to the pumping stage will build up a head and make a gas blow. Without a forced flow type separator, most of the gas and oil will blow through the tubing. This velocity will sometimes unseat the pump, thereby making it necessary to send out a pulling rig to reseat and space the pump, which causes additional operating expense. This same velocity may also blow the packing out of the stuffing box on the polished rod, and cause loss of production and possible property damage.

When a gas blow occurs in a well where a forced flow separator is being used, the gas/oil blows into the casing annulus and does not disturb the pump during the duration of the blow.
Poor Boy Gas Separator

A poor boy gas separator is used when rathole is limited. The poor boy gas separator consists of a slotted mud anchor or perforated nipple/mud anchor combination and a gas anchor (please refer to Fig. 2-17). The mud anchor is usually one to three joints of pipe with the same outside and inside diameters as the production string with the end
orange peeled closed. The mud anchor might be slotted at the top to allow fluid entry if a perforated nipple is not employed in conjunction with the mud anchor. The gas anchor is piping usually one inch (1”) in diameter and six to ten feet (6’-10’) in length with the end orange-peeled closed. Fluid entry is achieved through perforations or anchor ports placed in the bottom of the gas anchor. During normal pumping operations, fluid enters the perforated nipple or anchor ports in the mud anchor, travels down the annular space between the gas and mud anchors, and enters the pump via the gas anchor perforations or anchor ports.

Initial gas separation occurs at the mud anchor or perforated nipple-openings due to the pressure drop required to achieve entry coupled with the turbulence created as fluid flows into the separator.

Secondary gas separation occurs at the gas anchor openings due to the pressure drop required to enter the pump. The downward flow rate of the fluid inside the separator should be below the critical velocity in order to allow the secondary gas to escape into the casing. However, historical practices and procedures often do not ensure that critical velocity requirements are met, therefore, the separator does not function properly. Existing separators should be examined to ensure that the design accounts for the critical velocity of the produced fluid. Placement of the mud anchor or perforated nipple openings may be above or below the casing perforations, but most often the openings are placed above the perforations due to limited rathole.

As with the natural gas separator, the mud anchor openings should be placed twenty to thirty feet (20’-30’) above or below the uppermost or lowermost active perforation, to ensure that the openings are not in the turbulent zone of the wellbore. In association, gas evolution inside the gas anchor should be minimized by utilizing the largest diameter possible in design of the gas anchor, thereby minimizing friction pressure drop. Gas anchor size will be limited by mud anchor size which in turn is limited by casing size. Optimizing the design will require balancing trade offs in equipment sizes. When the rathole is too small for the installation of a natural gas separator, the poor
boy gas separator is the most widely utilized gas separator in sucker rod. This is because the poor boy gas separator has availability of materials and is very economic.

**Figure 2-16: Poor boy gas separator**

*Image of Poor Boy Gas Separator*

**Modified Poor Boy Gas Separator**

When rat hole is limited in a wellbore with large casing (usually greater than 4 1/2”) gas separation can be enhanced by modifying the poor boy gas separator. The modification involves the use of a mud anchor which has a larger outside diameter than the production string (Figure 2-17). Gas separation is enhanced because gas is forced out of solution due to an increase in velocity in the reduced casing/mud anchor annulus. In accordance, the gas anchor/mud anchor annulus becomes enlarged, and downward fluid velocity is minimized thereby improving secondary gas escape into the casing. The
probability of sticking the mud anchor is greatly increased with the modified poor boy gas separator.

Wellbore conditions should be carefully evaluated before placing the mud anchor below casing perforations. The modified poor boy gas separator should never be placed in an open hole environment. If wellbore conditions permit, the modified poor boy gas separator should be used instead of the poor boy gas separator because of superior performance.

Figure 2-17 Modified poor boy gas separator
The separators show below are the most popular, but there are many more. There are some variations such as the use of screens; this kind of separator is called the screen-type gas/liquid separators. This separator uses a screen that has proved to be effective if the two-phase fluid is clean. Experiments have shown, however, that the screen may clog quickly when used in an oil well environment.

A discussion of other separator designs is beyond the scope of this thesis. However for the sake of completeness Appendix C includes summaries of 42 patents of downhole gas separators.

Use of tubing anchors

A properly designed tubing anchor is another important factor in effecting proper downhole separation. Some tubing anchors fill the casing and have inadequate or practically no water courses (Figure 2-18). Free gas, trying to make its way up the casing annulus, must have adequate and unrestricted passage to prevent gas locking the pump. A small restriction can create a column of gaseous foam that builds up a back pressure, forcing more gas through the pump. The selection of tubing anchors with generous water courses is of utmost importance to permit free passage of gas (Figure 2-19).

Figure 2-18: Tubing anchor with inadequate or practically no water courses

Figure 2-19: Tubing anchor with generous water courses
3. EXPERIMENTAL FACILITIES

The tests were conducted at the laboratory of the Petroleum and Geosystems Engineering Department at The University of Texas at Austin.

All the tests were recorded with a digital camcorder to generate videos files that were later analyzed. The data generated in each test was saved in an Excel file and with this data, different graphs were generated to help analyze the behavior of the downhole gas separator being tested.

One of the objectives of this project was to find the best design and position for a downhole gas separator. In the oil industry, there are many different kinds of downhole gas separators, but still there exist many questions. Therefore, in order to address these issues, new ideas must be formulated. Field experience shows that some of the questions include the following:

1. Separator Position Relative to Perforations
   a. Above Perforations.
   b. In Perforations.
   c. Below Perforations.

2. Rod Pump vs PCP
   a. Rod Pump (Static Period during down stroke)
   b. PCP (no Static Period pump)

3. Intake port size (big vs small)
   a. Small openings (1/8” diameter anchor ports or perforations)
      - Obtains greater annular separation than large openings.
   b. Standard design-large openings
      - Minimizes pressure drop (gas bubble creation)
      - Allows counter flow of oil and gas.

4. Vent Holes: Standard design allows gas to escape due to counter flow with oil and water. Vent holes allow for an alternate path for gas to vent.
3.1 Testing

To try to find the “best” downhole gas separator, the apparatus must be tested under different conditions. These conditions are explained by the following:

1. INTAKE GEOMETRY
   a. Large openings vs. small openings.
   b. Total open area is the same that the tubing area (minimize the pressure drop).
   c. Size of separator/casing size.
   d. Separation Efficiency (gas vented through the annulus/total gas).

2. VENT HOLES/BAFFLE
   a. Hole size and ratio to intake area (separation impact)
   b. Do the vent holes vent gas or recirculate fluid?
   c. Does a reduction in area from the separator to vent hole location provide a differential pressure to allow flow out.

3. POSITION
   a. Above the perforations (gas and liquid entering wellbore from above the anchor ports).
   b. In front of the perforations (gas and liquid directed at intake anchor ports).
   c. Below Perforations (gas and liquid entering wellbore from below the anchor ports).

3.2 Design of the Well Model

To model the separator, an apparatus that simulates a producing well needed to be built in which different rates of water and air can be controlled to evaluate the performance of various separator designs. The design shown in Figure 3.3 simulates a producing well with a 14-foot long clear acrylic pipe (item 6) with a diameter of 6 inches.
Above the acrylic casing, there is a 40-foot long PVC casing (item 7) to provide sufficient hydraulic head to obtain the desired flow through the system.

One of the parameters to simulate is the position of the downhole separator relative to the formation perforations. One way to accomplish this is to move the separator. However, this is too complicated. This apparatus was built with several perforated zones that are activated by the opening or closing of the valves in the manifold; therefore, it is as if the position of the downhole gas separator were moving relative to the perforations.

The horizontal three-phase separator that is in the laboratory is used both as a storage tank for (the water that is flowing to the well) and as a separator for the return flow from the well model to separate the gas (air) that is going through the “pump” and to feed it to the output flow-meters.

Figure 3-1 shows the design of the Patterson Model downhole gas separator. It is a 6-foot clear acrylic pipe (item 2) with a diameter of 3 inches OD and 2.750 inches ID. It has 8 anchor ports (8 inches long and 1/8 inches wide). The anchor port width was one of the variables to be studied, starting with 1/8”. Later, it was adjusted to 1/4” and, finally, tested at 1/2”. In the upper part, there are four holes of 1/2” diameter. These holes allow the gas to escape from the separator. Inside the anchor, there is a dip tube. The other variable to be studied is the diptube diameter, the separators was tested with two different diameter of diptube (1” OD and 1 ½ “OD).

Figure 3-2 shows the design of the Echometer Model downhole gas separator. It is a 6-foot clear acrylic pipe (item 2) with a diameter of 3 inches OD and 2.750 inches ID. It has 4 ports (4 inches long and 2 inches wide). Inside the anchor, there is a dip tube. The diptube diameter is a variable to be studied therefore this model was tested with two different diameters of diptube (1” OD and 1 ½ “OD).

In the well, the water and the gas enter the well through the perforations (item 6). Part of this gas will be separated from the water and travel up the upper PVC casing (item 7) and vent to atmosphere. The hydrostatic pressure generated by the column of water and gas inside the PVC casing provides the energy to drive the return flow and water with
some gas will go through the separator (item 2) back to the tank from the outlet of the gas separator.

Flow control is achieved with the return valve by maintaining a constant Bottom Hole Pressure (BHP). Figure 3-3 shows how the system will work.

Table 3-1 and Table 3-2 show calculations of different hydrostatic columns that are needed to achieve different liquid rates. It is known that for tubes the flow is turbulent when the Reynolds Number is greater than 2100. Therefore, the system will work with a turbulent flow.

Table 1 shows the calculations when it is assumed that there is 100% water in the PVC casing, but in the casing there will be a mixture of water and air (the air that is separated and is going to the surface). Therefore, the density will be less than 1000 kg/m³. Table 2 shows the same calculations but with a density of the mix of 800 kg/m³.
Figure 3-1: Downhole gas separator (Patterson Model)

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Figure 3-2: Downhole gas separator (Echometer Model)

### Downhole Gas Separator

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<td>inches</td>
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Dimensions:
- OD: 3.000 inches
- ID: 2.750 inches
- OD Area: 7.068 inch²
- ID Area: 5.940 inch²
- Total Area: 32.000 inch²
- Number of holes: 4.000
- Longitude: 4.000 inches
- Width: 2.000 inches
- Area of each slot: 8.000 inch²
- Total Area: 32.000 inch²
- OD: 1.000 inches
- ID: 0.750 inches
- OD Area: 0.786 inch²
- ID Area: 0.442 inch²
- ID: 6.000 inches
- ID Area: 28.274 inch²
- Anchor/Dip Tube Area: 5.154 inch²
- Casing-Anchor Area: 21.206 inch²
Figure 3-3: Schematic of the experimental apparatus
Table 3-1: Calculations of different hydrostatic columns that are needed for different rates when the density of the fluid is 1000 kg/m³.

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<th>Oil</th>
<th>Voltubeinchoil (m³)</th>
<th>Pf (psi)</th>
<th>Density (1000 kg/m³)</th>
<th>Viscosity (1 cp)</th>
<th>Roughness (1.05-07)</th>
<th>P3 (psig)</th>
<th>Vtube (m³)</th>
<th>Rtube (psig)</th>
<th>P2 h (psig, ft)</th>
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Table 3-2: Calculations of different hydrostatic columns that are needed for different rates when the density of the fluid is 800 kg/m³.

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<th>Reduct/Outlet (psig)</th>
<th>P2 (psig)</th>
<th>Volute (m/s)</th>
<th>Reduct. (m/s)</th>
<th>Factor/Rupture</th>
<th>Volute (m/s)</th>
<th>P3 (psig)</th>
<th>Reduct. (m/s)</th>
<th>P4 (psig)</th>
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<td>5.52495</td>
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</table>

P2, P3 and P4 are the calculated pressures not including the kinetic losses. Because the kinetic losses are negative, it is better to design for the worst condition when the kinetic losses are zero.
In order to run tests at various rates, the upper casing length needs to be between 6-10 feet, depending on how much air is in the hydrostatic column. Therefore, 14 feet should be enough to try to control the return flow. In Figure 3-4 and Figure 3-5, the support frame for the casing and the upper casing can be seen.

![Figure 3-4: Support frame for the casing](image1)

![Figure 3-5: Upper casing](image2)

3.3 Well Model

Figure 3-6 shows the casing used to simulate the perforated section. This section of casing is 6 inches ID and 6.5 ft high. The total length of the perforated casing is 10 feet (the casing consists of two pieces, one is 6.5 ft and the other is 3.5 ft).

The casing has four perforations per foot. Through these perforations, water mixed with gas are injected (simulating the production in any well flowing below bubble
point pressure). Figure 3-7 shows these perforations and the steel frame used to support the casing vertically.

**Figure 3-6: Perforated section in the casing**

![Perforated section in the casing](image)

**Figure 3-7: Perforations and the steel frame used to support the casing vertically**

![Perforations and the steel frame used to support the casing vertically](image)
3.4 Flow System

As can be seen in the diagram (Figure 3-3), there is a 30-foot long casing, 10 inches ID, to simulate the upper part of the well and store sufficient liquid above the gas separator. This casing is of PVC material. Figure 3-3 shows the flow diagram of the apparatus. It consists of:

- **Tank:** A horizontal separator is used as the tank (Figure 3-8). The water is stored in this tank the water with some gas comes back to the tank from the liquid outlet of the gas separator. The horizontal separator is very useful in measuring how much air is separated with an air meter which is put in the gas exit. Therefore, measuring how much air is injected and how much air is coming out with the liquid through the separator dip tube, the efficiency of the downhole gas separator can be calculated.

**Figure 3-8: Tank (horizontal separator)**
• **Centrifugal pumps**: They pump the water from the tank to the well. There are two pumps (one red and one blue). The red pump can pump up to 700 barrels per day and both pumps together can pump up to 1100 barrels per day.

![Figure 3-9: Centrifugal pumps](image)

• **Mixer**: Where the air mixes with the water from the tank.

• **Manifold**: It is used to simulate that the downhole separator is positioned in front, above or below the perforations.

The entire casing has perforations and the manifold is used to control which perforations are open to the flow of the mixture of water and air.
• **Two air meters:** One meter measures how much air is being introduced into the well (this is before the air enters the mixer). The other air meter is at the exit of the tank (horizontal separator) and it measures how much air is coming out with the water.

Figure 3-11 shows the air meter that is at the exit of the horizontal separator. This meter measures the air that would be entering the pump (the air that is not separated by the downhole gas separator so it measures how much air is coming out with the water).

Figure 3-12 shows the air meter that is at the entrance of the manifold. This meter measures the flow rate of air that enter into the well as a percentage of full scale (100% is equal 16.42 MCFD). This measurement is at the specific meter pressure. Therefore, the general gas equation is used to convert the gas volumetric rate in the meter to the gas rate flowing into the well at standard conditions.
From Figure 3-3, one can see that the water is coming from the tank. It mixes with the air in the mixer, and all together will go through the perforations.

3.5 Building the Components for the Well Model

Figures 3-13 and 3-14 show the part of the casing that faces the downhole gas separator. It has eight perforations where the mixture of water and air pass through.
Therefore, there are 8 perforations per foot, depending on the configuration given. It can be 2 perforations per foot, 4 perforations per foot or any configuration that is desired. This configuration can be managed with the manifold because the manifold has a valve for each perforation.

Figure 3-13: Part of the casing that faces the downhole gas separator

Figure 3-14: Perforation on the part of the casing that faces the downhole gas separator
To connect the transparent casing with the 30 foot casing of PVC, a connecter is needed due to the fact that the PVC has a diameter of 8 inches and the transparent casing has a 6-inch diameter.

The design was changed in some aspects, for example the mixer and the manifold is now one component. In the beginning, the idea was to mix the water and the air before entering the manifold. However, it was decided that it is better to mix the water and the air in the manifold in order to try to make a uniform mixture.

3.6 Building the Downhole Gas Separator

Figures 3-15 and 3-16 show the downhole gas separator; this is the same one that was described previously in Figure 3-2a.

To connect the downhole gas separator and the tubing, the connecter that is shown in Figure 3-17 is used.

**Figure 3-15: Complete view of the downhole gas separator**
Figure 3-16: Anchor ports and holes in the downhole gas separator

Figure 3-17: Downhole gas separator connector
3.7 Putting all the parts together

To start running the experiments, all of the parts needed to be put together. The downhole gas separator is connected to the tubing and later, the casing of the last part of the casing column is connected. Figure 3-18 shows the acrylic tubing that will be connected to the downhole gas separator.

Figure 3-19 shows the joint between the acrylic tubing and the downhole gas separator. Figures 3-20 and 3-21 show the downhole gas separator. It is held by the connecter that joins the acrylic tubing and the downhole gas separator.

Figure 3-18: Tubing that will be connected to the downhole gas separator.

Figure 3-19: Joint between the tubing and the downhole gas separator.
Because the downhole gas separator will have water inside, the connector with the O’rings could not hold the separator. Therefore, to keep the separator connected to the tubing and centralized there is a polished rod that supports and centralizes the apparatus.

**Figure 3-20:** Tubing connected to the downhole gas separator.

**Figure 3-21:** Downhole gas separator held by the connector that joins the tubing.
4. EXPERIMENTAL PROCEDURE

4.1 Data Acquisition

The acquisition of relevant data is the basis for the analysis of the behavior of the different downhole gas separators models studied in this project.

**Gas Rate injected into the well**

The flow of gas into the well is measured by a Fisher & Porter variable area flow meter (model No. 10A4557X). Compressed air is used to simulate the gas in real wells; therefore, the flow meter measures the air rate entering the well. The scale of this flow meter is a percentage, from 0% (0 MCFD) to 100% (16.42 MCFD). In the experiments four flow rates corresponding to 90%, 60%, 30% and 10% are used. The flow rate is measured at the pressure of the meter that is read using a Daniel pressure transducer and then converted to standard conditions.

**Volume of the gas injected into the well**

The volumetric actual rate of gas injected into the well is a function of pressure and temperature. The conversion is made by using the general gas equation \( P_1V_1 = P_2V_2 \) assuming that there is no change in temperature as the gas flows through the system.

**Liquid Rate Injected into the well**

The flow meter used to read the rate of liquid injected into the well is a Floco (Model No ITT Barton 308K), positive displacement meter for which each revolution of the needle represents 0.1bbl. The liquid rates used for this project are from 100 to 750 bbl/day.
**Casing Pressure**

The pressure in the casing, measured in psig, is a control pressure and is used as an indication of stable flow conditions. For these experiments, the pressure in the casing was controlled at two average values of 5 and 10 psi at stable conditions. The pressure level was limited by the height (30 feet) of the casing riser that was available to contain the gaseous liquid column in the well at the largest gas rate of 118.70 MSCFD without overflowing.

**Ports Pressure**

Fluid enters into the downhole gas separator through the ports, which can have different geometries depending on the separator model. A manometer is placed in the casing in front of the ports. Pressure measurements are done in psi.

**Separator Exit Pressure**

The pressure at the exit of the separator (that would correspond to the pump intake pressure in the real well) is measured using a pressure/vacuum gage, in psig for positive values and in inches of Mercury for negative values (vacuum). This pressure is important because it is used to calculate the pressure drop through the separator system. For field application, this pressure will be considered to be also equal to the pressure in the pump assuming there are no additional pressure losses through the intake valve. Pressure drop in the system depends on the geometry of the diptube. For a small diptube diameter, the pressure drop is high and for a large diptube diameter the pressure drop is low.

**Gas Rate Flowing Through Gas Separator**

The flow rate of the gas (air) that is not separated by the separator and is produced with the liquid (water) is registered on one of three flow meters each covering different ranges:
• OMEGA FL-3820C (0-150 mm) from 0 to 63 SCFD
• OMEGA FL-3839ST (0-150 mm) from 0 to 886 SCFD
• OMEGA FL 50000 (0-4.5 inches) from 0 to 6480 SCFD.

The efficiency of the separator is computed by comparing the gas rate flowing into the well to the gas rate flowing through the downhole gas separator.

The data acquired during one series of tests is entered on a spreadsheet to save the data and calculate new parameters such as superficial liquid velocity in the separator, superficial liquid velocity and superficial gas velocity in casing, and the gas rate through the separator.

4.2 Experimental Procedure

The experiment simulates an oil well producing with gas interference. Since the experiment is carried out in an indoor laboratory the fluids used are water simulating the liquid (oil and water) and air simulating the gas. A downhole gas separator is placed inside the wellbore and a group of tests for each casing pressure (5 and 10 psi), each separator model (Patterson’s and Echometer’s models) and each position of the downhole gas separator (in front, under and above the perforations) are performed.

Water is injected at different rates, from 100 to 700 BBD, depending on the requirements of the experiments, with rates of air mixed with water injected, from 10 up to 110 MSCFD.

The following steps were followed to ensure an adequate performance of the experiment (Figure 4-1 illustrates the steps described below):
1. **Open the respective valves (V1) in the manifold:** To select the position of injection with respect to the separator entry ports (in front, under or below the perforations), the manifold has eleven valves. Each valve is attached to a hose that connects the manifold to a perforation on the casing of the well. Therefore, to simulate placing the downhole gas separator in front of the perforations, it is necessary to open the valves of the perforations that are located in front of the ports of the downhole gas separator. If it is desired to simulate placing the entry ports of the downhole gas separator below the perforations, the valves connected to the perforations located below the ports must be opened.

2. **Open the release valve (V7) and set the manometer at zero:** A release valve (V7) is placed next to the manometer (M3), which reads the tubing pressure. Sometimes, since this pressure has negatives values (vacuum), it is recommended that, before starting a new group of tests, this valve be opened to equalize the pressure to atmospheric conditions.

3. **Open the gas exit valve (V9) in the Surface Separator:** The separator at the surface is a three phase separator (oil, water and gas). This large separator needs to be at atmospheric pressure before initiating the tests.

4. **Turn on the pump (P1):** Using one centrifugal pump, from 0-750 barrels/day can be pumped. If it is necessary to pump more than 750 BBD. Turning on the other pump the rate may be increased up to 1000 BBD.

5. **Adjust the pump manifold valve (V2) to obtain the rate desired:** A valve (V2) that controls the flow of the liquid into the well is placed between the pump and the manifold. If this valve (V2) is totally open, the rate of liquid entering the well can reach up to 750 BBD. Depending on how much liquid rate is desired, this valve (V2) can be opened to different positions.

6. **Read the Flow Meter (F1) for the liquid:** The Floco Meter (F1) measures the liquid entering the well, measured in 0.1bbl increments. This data is saved in the second column of the spreadsheet, and, in the third column, it is converted to barrels/day.
7. **Set Casing Pressure (Pc):** Casing pressure is an important parameter for comparing tests at different conditions. Casing pressure shows the hydrostatic fluid column that is above the manometer. A valve (V8) placed at the return line to the tank regulates the return of the fluid. This valve (V8) is opened and closed depending on how much fluid above the manometer (M1) is needed. This fluid column depends on the difference of the liquid rate entering into the well and the liquid returning to the surface separator (tank). It is necessary to manipulate this valve (V8) until the desired casing pressure is reached and becomes constant. The pressure is initially set when flowing 100% water to get stable casing pressures of 5 or 10 psi.

8. **Open the air line:** In order to start injecting air into the well, the valve (V6) that is placed in the air line, which controls the air coming into the mixer, must be opened.

9. **Set the percentage of air:** For this project 90%, 60%, 30% and 10% of air (100% is equal to 16.42 MCFD) is used. The gas rate is controlled by a valve downstream (V5) of the flow meter, which sets the quantity of air that is required for the well in each test.

10. **Open the air valve (V3) at the entrance of the manifold:** There is a valve (V3) in the line that connects the air supply to the manifold. To get a homogeneous mixture of water and air, it is necessary to open this valve that permits the air and water to mix in the manifold before the entering the well. The fluid entering the well is a combination of water and air; the quantities of the water and air depend on each test.
Figure 4-1: Steps followed to ensure an adequate performance of the experiment
11. **Keep controlling the valve (V8) of the Casing Pressure to get stable conditions:** In step seven, the casing pressure was set at 5 or 10 psi (depending on the experiment requirements), but this value was reached with 100% water. In step eleven, the fluid is a mixture of water and air; consequently, the hydrostatic column has a gradient less than 0.433 lb/ft (water gradient). Later on, when the desired casing pressure is reached and there is not too much variation, it is the moment at which stable conditions are present (casing pressure, gas rate and liquid rate constant). The valve (V8) placed at the return line to the tank must be manipulated again until the casing pressure desired is reached and constant. The hydrostatic column pressure depends on the gas rate and liquid rate to reach the same pressure for different tests. In the case of 5 psi, for 90% gas rate, the hydrostatic column is higher than for 10% gas rate at the same liquid rate.

12. **Wait at least 20 minutes or until all rates stabilize:** It is recommended to wait at least twenty minutes to stabilize each test. Less than twenty minutes is not appropriate because of the variation in the casing pressure, tubing pressure, ports pressure and in the gas rate going through the downhole gas separator.

13. **Read the Casing Pressure (M1), Ports Pressure (M2), Tubing Pressure (M3) and, Meter Pressure (M4):** Save these readings on the spreadsheet. These values are important for calculations of other parameters.

14. **Read the gas through the separator (F2):** The gas rate that flows through the downhole gas separator can be read with one of the three flow meters: OMEGA FL-3820C (0-150 mm), OMEGA FL-3839ST (0-150 mm) and OMEGA FL 50000 (0-4.5 inches).

    Change the rate of the liquid and repeat all the steps before the next test. It is better to start with the largest liquid and gas rate and later reduce the rates to complete the tests. If the tests begin with the smallest liquid and gas rates, it takes more time to reach the stabilization of the tests (forty minutes for each test).
Table 4-1 shows the testing range for gas rate and liquid rate of each downhole gas separator model.

**Table 4-1: Maximum and minimum gas and liquid rate for all of the separators tested in this project.**

<table>
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<th>SEPARATOR MODEL</th>
<th>Maximum Liquid Rate BBD</th>
<th>Minimum Liquid Rate BBD</th>
<th>Maximum Superficial Liquid Velocity in Separator inches/second</th>
<th>Minimum Superficial Liquid Velocity in Separator inches/second</th>
<th>Maximum Gas Rate MSCFD</th>
<th>Minimum Gas Rate MSCFD</th>
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5. Discussion of Experimental Results

The performance of eleven downhole gas separator models was studied: seven Patterson models, three Echometer models and one Bucket model. The data generated from these tests was saved on a spreadsheet, plotted on graphs and analyzed to understand the behavior of the separator models. Pictures of the flow, at the separator dip tube, for each data point are included for visual observation. The downhole gas separators were tested for different conditions; these conditions were position of the anchor ports, geometry of the anchor ports, and geometry of the dip tube and pressure effect.

5.1 Position of the Anchor Ports (Slots) Relative to the Perforations

The downhole gas separators were tested in different positions such as: fluid entering above, in front or below the anchor ports.

5.1.1 Patterson Models

Since the effect, of position of the anchor ports, was similar for all the Patterson models tested, Patterson 2 (anchor ports = 8” x ¼” & dip tube = 1”) was chosen for discussion of the position of the anchor ports.

Figure 5-1 (5-1a and 5-1b) shows the Patterson 2 model. It is observed in the pictures that Patterson 2 has eight anchor ports. Each anchor port is 8 inches long and 1/4 inches wide. The dip tube is 1 inch OD, 3/4 inches ID and has black lines spaced at 2 inch intervals to help us analyze the behavior and velocities of the gas bubbles.

The Patterson models, with the exception of Patterson 7, have eight anchor ports 8” long and a width depending on the model between 1/8” and 3/4”. Two different dip tube diameters were used (OD=1” and 1.5”). The only Patterson model that does not have eight anchor ports is Patterson 7, which has four. It is similar to Patterson 3, but the top anchor ports are closed.
All the Patterson models have four holes encircling the top of the anchor spaced at 90 degrees on the circumference. These holes are for the gas to escape to the annulus. The characteristics of the geometry of this separator are detailed in Figure 5-2.

**Fluid Entering in Front of the Anchor Ports**

Table 5-1 shows the data obtained from the test and the data calculated for Patterson 2 when the fluid is entering in front the anchor ports and the casing pressure is 10 psi. The explanation for each column of this table is in Appendix E. The same table format is used for all the separators.

**Figure 5-1: Patterson 2**

![Figure 5-1a](image1)

![Figure 5-1b](image2)
# Geometry of Patterson 2

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<td>Area of each slot</td>
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<table>
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<tr>
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<td>inches</td>
</tr>
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<td>ID Area</td>
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<td>inch²</td>
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<td>ft²</td>
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<td></td>
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<td>ft²</td>
</tr>
<tr>
<td>Casing-Anchor</td>
<td>21.206</td>
<td>inch²</td>
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<td></td>
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<td>ft²</td>
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<td>Test N°</td>
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<td>Liquid Rate</td>
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<td>-------------</td>
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<td>%</td>
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<tr>
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<tr>
<td>7</td>
<td>85.9</td>
<td>90%</td>
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SEPARATOR TYPE: Patterson 2

OD DIP TUBE = 1"
NUMBER OF ANCHOR PORTS = 8
DIMENSIONS OF THE ANCHOR PORTS = 8" x 1/4"
FLUID ENTERING IN FRONT THE ANCHOR PORTS
Pc = 10 psi

Figure 5-3a
Figure 5-3a shows a plot of gas rate through separator (Z axis) as a function of superficial gas velocity in casing annulus (Y axis) and superficial liquid velocity inside separator (X axis). This kind of graph will be presented for all gas separators discussed in this chapter.

Figure 5-4 shows pictures of the flow in the separator corresponding to each data point found Table 5-1. The pictures show the gas going through the entrance of the dip tube. Pictures, like these, will be shown for all the gas separators discussed in this chapter.

It is noticed on the graph (Figure 5-3a) that the maximum gas rate through separator is 0.132 MSCFD (Figure 5-4, Test 1), which occurs when the superficial liquid velocity inside separator is 14.78 inches/second and the superficial gas velocity in casing annulus is 55.77 inches/second.

The graph shows three kinds of groups of trend curves. One is the superficial liquid velocity inside the separator curves, another is the superficial liquid gas velocity inside separator curves and the other is the zero curve. The zero curve contains the values of the superficial gas velocity in casing annulus and the superficial liquid velocity inside separator for which the gas rate through separator is almost zero.

From this point on, the superficial liquid velocity inside separator curve will be called liquid curve, the superficial liquid gas velocity inside separator curve will be called gas curve, the superficial liquid velocity inside separator will be called liquid velocity, the superficial gas velocity in casing annulus will be called gas velocity and the gas rate through separator will be called gas in separator in order to abbreviate the terms.

Decreasing the liquid velocity, the gas rate in separator will decrease (this is very clear in the liquid curve). When the liquid velocity is decreased from 14.78 inches/second to 12.51 inches/second, the gas rate in separator is reduced from 0.132 MSCFD to 0.033 MSCFD (Figure 5-4, Test 5). It is observed in Figure 5-3a that when the liquid velocity is between 5.96 and 2.19 inches/second the gas rate in separator is almost zero (Figure 5-4, Test 6 and 7). Liquid velocity values for design will be any value less than 12.51
inches/second because at this velocity for any gas velocity the gas rate in separator will be almost zero (zero curve).

Decreasing the gas velocity in the well’s annulus causes the gas rate in separator to decrease. When the gas velocity is decreased from 55.77 inches/second to 38.08 inches/second, the gas rate in separator is reduced from 0.132 MSCFD to 0.108 MSCFD (Figure 5-4, Test 2). This behavior is noticed in the gas trend curve.

Figure 5-3a shows the gas rate through separator (Z axis) from 0 to 0.95 MSCF. In the following discussion the separator performance will be plotted on a vertical scale from 0 to 2.0 MSCF/D (such as Figure 5.3b) in order to be able to visually compare the performance of all the separators that were tested.

**Figure 5-3b**
Figure 5-4: Patterson 2 tests (Fluid entering in front the anchor ports at \( P_c = 10 \text{ psi} \))
Table 5-2 shows the data obtained from the tests and the data calculated for Patterson 2 when the fluid is entering below the anchor ports and the casing pressure is 10 psi.
Table 5-2

SEPARATOR TYPE: Patterson 2
OD DIP TUBE= 1"
NUMBER OF SLOTS=8
DIMENSIONS OF THE SLOTS=8" x 1/4"
FLUID ENTERING BELOW THE ANCHOR PORTS

| Test N° | Floco | Liquid Rate | Gas Rate MCF | Gas Rate MSCF | Annulus Pressure Maximum | Annulus Pressure Minimum | Ports Pressure Maximum | Ports Pressure Minimum | Tubing Pressure Maximum | Tubing Pressure Minimum | Superficial Liquid Velocity in Separator | Superficial Liquid Velocity in Casing | Superficial Gas Velocity in Casing | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | 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through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through 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Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate 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SEPARATOR TYPE: Patterson 2

OD DIP TUBE = 1"
NUMBER OF ANCHOR PORTS = 8
DIMENSIONS OF THE ANCHOR PORTS = 8" x 1/4"
FLUID ENTERING BELOW THE ANCHOR PORTS
Pc = 10 psi

Figure 5-5
Increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate flowing through the separator. 

In Figure 5-5, it is noticed that the liquid flow trend curve is almost a horizontal line from 50.20 inches/second to 19.97 inches/second when the liquid velocity is between 11.97 to 12.47 inches/second. Similar behavior of these points is shown in the pictures for Test 1, Test 2 and Test 3 in Figure 5-6. In test 1 and test 2 a phenomenon occurs that we termed “waterfall” (greater detail in section 5.5.2).

Liquid velocity values for design can be obtained from the zero curve. For example, for designing a separator at gas velocity equal to 52.35 inches/second, the liquid velocity must be less than 2.14 inches/second (Figure 5-6, Test 6).

Figure 5-6: Patterson 2 tests (Fluid entering below the anchor ports at Pc =10 psi)
Table 5-3

SEPARATOR TYPE: Patterson 2
OD DIP TUBE= 1"
NUMBER OF SLOTS= 8
DIMENSIONS OF THE SLOTS= 8" x 1/4"
FLUID ENTERING ABOVE THE ANCHOR PORTS

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<th>Floco Meter</th>
<th>Liquid Rate</th>
<th>Gas Rate (MCF)</th>
<th>Gas Rate (MSCF)</th>
<th>Annulus Pressure Maximum</th>
<th>Annulus Pressure Minimum</th>
<th>Ports Pressure Maximum</th>
<th>Ports Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Tubing Pressure Minimum</th>
<th>Superficial Liquid Velocity in Separator</th>
<th>Superficial Gas Velocity in Casing</th>
<th>Gas Rate through Separator</th>
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<td>3.5</td>
<td>6.0</td>
<td>14.8</td>
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<td>negative</td>
<td>15.06</td>
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<td>5.5</td>
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<td>3.72</td>
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<td>0.00</td>
<td>0.000</td>
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</table>

FLUID ENTERING ABOVE THE ANCHOR PORTS

SEPARATOR TYPE: Patterson 2
OD DIP TUBE= 1"
NUMBER OF SLOTS= 8
DIMENSIONS OF THE SLOTS= 8" x 1/4"
FLUID ENTERING ABOVE THE ANCHOR PORTS

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Floco Meter</th>
<th>Liquid Rate</th>
<th>Gas Rate (MCF)</th>
<th>Gas Rate (MSCF)</th>
<th>Annulus Pressure Maximum</th>
<th>Annulus Pressure Minimum</th>
<th>Ports Pressure Maximum</th>
<th>Ports Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Tubing Pressure Minimum</th>
<th>Superficial Liquid Velocity in Separator</th>
<th>Superficial Gas Velocity in Casing</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.9</td>
<td>76.64</td>
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<td>0.00</td>
<td>11.0</td>
<td>99</td>
<td>4.0</td>
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<td>12.5</td>
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<td>3.72</td>
<td>8.69</td>
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<td>0.000</td>
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</table>

85
Fluid Entering Above the Anchor Ports

This corresponds to the configuration known as “Natural Gas Anchor”. Table 5-3 shows the data obtained from the tests and the data calculated for Patterson 2 when the fluid is entering above the anchor ports and the casing pressure is 10 psi.

Figure 5-7

**SEPARATOR TYPE: Patterson 2**

- OD DIP TUBE = 1"
- NUMBER OF ANCHOR PORTS = 8
- DIMENSIONS OF THE ANCHOR PORTS = 8" x 1/4"
- FLUID ENTERING ABOVE THE ANCHOR PORTS
- $P_c$ = 5 & 10 psi
Figure 5-7 shows pictures of the dip tube of Patterson 2 when the fluid is entering above the anchor ports, the liquid velocities are between 14.90 and 15.84 inches/second and the gas velocities are from 0 to 58.30 inches/second. It is observed that there is almost no gas entering the dip tube.

5.1.2 Analysis of the effect of the Position of the Anchor Ports Relative to the Perforations on the performance of the Patterson Models

From these tests, it can be concluded that when the fluid is entering above the anchor ports, the volume of gas entering the downhole gas separator is virtually zero. It was observed that to get this effect is necessary to have only a foot of distance between the top of the anchor ports and the bottom of the perforations.

When the fluid is entering in front of the anchor ports, the maximum gas rate in separator is 0.132 MSCFD when the gas injected into the well is 109.02 MSCFD (gas velocity = 55.77 inches/second) and the liquid rate is 678.18 BBD (liquid velocity = 14.78 inches/second).

The most critical position is when the fluid is entering below the anchor ports. The maximum gas rate in separator is 0.95 MSCFD when the gas rate injected into the
well is 103.72 MSCFD (gas velocity = 50.20 inches/second) and the liquid rate is 558.14 BBD (liquid velocity = 12.17 inches/second).

Figure 5-8 shows the plot of the maximum gas rate in separator value when the fluid is entering below the anchor ports (0.95 MSCFD) in Figure 5-3 (fluid entering in front the anchor ports). This shows that at the same conditions, but at different positions, the gas rate going through the downhole gas separator is increased twelve times. In this position, the “waterfall” phenomenon is observed.

Figure 5-8: Patterson 2 (Fluid entering in front the anchor ports at Pe = 10 psi)
5.1.3 Echometer Models

Since the observed effect was similar for all the Echometer models tested, Echometer 1 (4”x2” & dip tube = 1”) was chosen for discussion of the effect of the position of the anchor ports relative to the fluid entry into the well.

Figure 5-9 (5-9a and 5-9b) shows the Echometer 1 model. It is observed in the pictures that Echometer 1 has four anchor ports. Each anchor port is 2 inches long and 4 inches wide. The dip tube is 1 inch OD and 3/4 inches ID.

The Echometer models (with the exception of Echometer 3) have four anchor ports. Two different dip tube diameters were used (OD=1” and 1.5”). Echometer 3 has two anchor ports, similar to Echometer 1, but the top anchor ports are closed. The characteristics of the geometry of this separator are detailed in Figure 5-10.

Fluid Entering in Front of the Anchor Ports

Table 5-4 shows the data obtained from the test and the data calculated for Echometer 1 when the fluid is entering in front the anchor ports and the casing pressure is 10 psi.

Figure 5-9: Echometer 1

Figure 5-9a

Figure 5-9b
Figure 5-10: Geometry of Echometer 1

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<td>Liquid Rate</td>
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<td>---------------</td>
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**Separation Type:** Echometer 1

**OD Dip Tube:** 1"

**Number of Slots:** 4

**Dimensions of the Slots:** 2" x 4"

**Fluid Entering in Front the Anchor Ports**

Date: 7/9/2004
SEPARATOR TYPE: Echometer 1

OD DIP TUBE = 1"
NUMBER OF ANCHOR PORTS = 4
DIMENSIONS OF THE ANCHOR PORTS = 2" x 4"
FLUID ENTERING IN FRONT THE ANCHOR PORTS
Pc = 10 psi

Figure 5-11

Superficial Gas Velocity in casing annulus (in/sec)
Superficial Liquid Velocity inside Separator (in/sec)
Gas Rate through Separator (MSCF/day)
Increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate flowing through the separator. In Figure 5-11, it is noticed that when the liquid velocity is between 10.76 and 11.04 inches/second, the gas rate in separator increases from 0.168 MSCFD to 0.897 MSCFD (liquid trend curve). Figure 5-12 (Tests 1, 2, 3 and 4) shows this variation of the gas rate in separator. When the liquid velocity is 10.77 inches/second and gas velocity is 57.17 inches/second, the “waterfall” phenomenon was observed (Figure 5-12, Test 1). When the liquid velocity is between 6.25 to 6.31 inches/second, the gas rate in separator is almost zero (Figure 5-12, Tests 5, 6 and 7). When the liquid velocity is 2.33 inches/second and the gas velocity is 58.19 inches/second, the gas rate in separator is zero (Figure 5-12, Test 8).

Figure 5-12: Echometer 1 tests (Fluid entering in front the anchor ports at Pc=10psi)
Fluid Entering Below the Anchor Ports

Table 5-5 shows the data obtained from the tests and the data calculated for Echometer 1 when the fluid is entering below the anchor ports and the casing pressure is 10 psi.
### Table 5-5

**SEPARATOR TYPE:** Echometer 1  
**OD DIP TUBE= 1”**  
**NUMBER OF SLOTS= 4**  
**DIMENSIONS OF THE SLOTS= 2” x 4”**  
**FLUID ENTERING BELOW THE ANCHOR PORTS**

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<th>Gas Rate</th>
<th>Gas Rate MCF</th>
<th>Annulus Pressure</th>
<th>Annulus Pressure Minimum</th>
<th>Ports Pressure</th>
<th>Ports Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Tubing Pressure Minimum</th>
<th>Superficial Liquid Velocity in Separator</th>
<th>Superficial Liquid Velocity in Casing</th>
<th>Superficial Gas Velocity in Casing</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
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**Date:** 7/12/2004
SEPARATOR TYPE: Echometer 1

OD DIP TUBE = 1"
NUMBER OF ANCHOR PORTS = 4
DIMENSIONS OF THE ANCHOR PORTS = 2" x 4"
FLUID ENTERING BELOW THE ANCHOR PORTS
Pc = 10 psi

Figure 5-13

Gas Rate through Separator (MSCF/day)

Superficial Gas Velocity in casing annulus (in/sec)

60 45 30 15 0

Superficial Liquid Velocity inside Separator (in/sec)

75 0 4 8 12 16

75 60 45 30 15 0
Increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate flowing through the separator.

In Figure 5-13, it is noticed that when the liquid velocity is between 11.79 and 12.04 inches/second, the gas rate in separator increases from 0.766 MSCFD to 1.094 MSCFD (liquid curve). These differences of gas rate in separator are observed in Figure 5-14 (Tests 1, 2, 3 and 4). It is observed that when the liquid velocity is between 5.95 and 5.99 inches/second, the gas rate in separator increases from 0.269 MSCFD to 0.628 MSCFD. Figure 5-14 (Tests 5, 6 and 7) does not show these differences very clearly.

Liquid velocity values for design can be obtained from the zero curve. For example, for designing a separator at gas velocity equal to 57.66 inches/second, the liquid velocity must be less than 2.67 inches/second (Figure 5-14, Test 8). The waterfall phenomenon was observed in Test 1 (Figure 5-14).

**Figure 5-14: Echometer 1 tests (Fluid entering below the anchor ports at Pc = 10 psi)**
Fluid Entering Above the Anchor Ports

Table 5-6 shows the data obtained from the tests and the data calculated for Echometer 1 when the fluid is entering above the anchor ports and the casing pressure is 10 and 5 psi.
| Test N° | Flocc N° | Liquid Rate (sec/0.1BBl) | BBD | % | OD | D (psig) | D (psig) | % | °Hg | °Hg | psi | psi | psi | psi | °Hg | psi | psi | Inches/sec | Inches/sec | FL-3820C | FL-3830ST | FL-50000 | MSCF | Comments |
|---------|----------|--------------------------|-----|---|----|---------|---------|---|-----|-----|-----|-----|-----|-----|-----|-----|----------|----------|----------|----------|----------|-------|----------|
| 1       | 13.1     | 658.54                   | 90% | 14.78 | 108.68 | 109.28 | 6.0 | 4.5 | 3.5 | 2.0 | -4.0 | -4.0 | 14.38 | 3.49 | 71.01 | 0 | 0.000 |
| 2       | 14.3     | 604.20                   | 90% | 14.78 | 108.31 | 108.92 | 10.2 | 9.0 | 7.5 | 6.0 | 3.5 | 2.7 | 13.17 | 3.20 | 56.97 | 0 | 0.000 |

**Table 5-6**

**SEPRACTOR TYPE: Echometer 1**

**OD DIP TUBE= 1”**

**NUMBER OF SLOTS=4**

**DIMENSIONS OF THE SLOTS= 2” x 4”**

**FLUID ENTERING ABOVE THE ANCHOR PORTS**
Figure 5-15 shows pictures of the dip tube of Echometer 1 when the fluid is entering above the anchor ports. It is observed that there is almost no gas entering the dip tube. These tests were made with two different casing pressures, one with a pressure of 5 psi (Figure 5-15, Test 1) and the other with a pressure of 10 psi (Figure 5-15, Test 2).

The liquid and gas rates used for these tests were the maximum achievable with the experimental set-up in order to analyze the worst-case scenario; therefore, if in the worst case the gas rate through separator is almost zero, it was not necessary to conduct more tests at a lower gas or liquid rate.

5.1.4 Analysis of the effect of the Position of the Anchor Ports Relative to the Perforations on the performance of the Echometer Models

Similar to the Patterson models, from these tests, it can be concluded that when the fluid is entering above the anchor ports, the volume of gas entering the downhole gas separator is virtually zero. It was observed that to get this effect it is necessary to have
only a foot of distance between the top of the anchor ports and the bottom of the perforations.

When the fluid is entering in front of the anchor ports, the maximum gas rate in separator is 0.897 MSCFD. This occurs when the gas injected into the well is 109.18 MSCFD (gas velocity = 57.17 inches/second) and the liquid rate is 494 BBD (liquid velocity = 10.77 inches/second).

Figure 5-16: Echometer 1 (Fluid entering in front the anchor ports at Pc = 10 psi)

The most critical position is when the fluid is entering below the anchor ports. The maximum gas rate in separator is 1.094 MSCFD when the gas rate injected into the well is 108.23 MSCFD (gas velocity = 51.11 inches/second) and the liquid rate is 540.68 BBD (liquid velocity = 11.79 inches/second).
Figure 5-16 shows the plot of the maximum gas rate in separator value when the fluid is entering below the anchor ports (1.094 MSCFD) in Figure 5-11 (fluid entering in front the anchor ports). This shows that at the same conditions, but at different positions, the gas rate going through the downhole gas separator is increased 1.42 times.

When the fluid is entering below and in front of the anchor ports, the waterfall phenomenon is observed.

5.1.5 Bucket Model

This model has a single anchor port (6” x 3”). A 1.5” diameter dip tube was used. The dip tube is decentralized (Figure 5-17).

The characteristics of the geometry of this separator are detailed in Figure 5-18. Table 5-7 shows the data obtained from the test and the data calculated for the Bucket model when the fluid is entering in front the anchor ports and the casing pressure is 10 psi.

**Figure 5-17: Bucket**

**Figure 5-17a**

**Figure 5-17b**

Fluid Entering Above the Anchor Ports

Table 5-7 shows the data obtained from the tests and the data calculated for the Bucket model when the fluid is entering in front the anchor ports and the casing pressure is 10psi.
Figure 5-18: Geometry of Bucket separator

### GAS ANCHOR

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</thead>
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<td>inches</td>
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</tr>
<tr>
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<td>inch²</td>
</tr>
<tr>
<td></td>
<td>0.041</td>
<td>ft²</td>
</tr>
</tbody>
</table>

### SLOT

<p>| | | |</p>
<table>
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<tr>
<th></th>
<th></th>
<th></th>
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<tbody>
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</tr>
<tr>
<td>Longitude</td>
<td>6.000</td>
<td>inches</td>
</tr>
<tr>
<td>Width</td>
<td>3.000</td>
<td>inches</td>
</tr>
<tr>
<td>Area of each slot</td>
<td>18.000</td>
<td>inch²</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>ft²</td>
</tr>
<tr>
<td>Total Area</td>
<td>18.000</td>
<td>inch²</td>
</tr>
<tr>
<td></td>
<td>0.125</td>
<td>ft²</td>
</tr>
</tbody>
</table>

### DIP TUBE INSIDE THE ANCHOR

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>OD</td>
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<td>inches</td>
</tr>
<tr>
<td>ID</td>
<td>1.280</td>
<td>inches</td>
</tr>
<tr>
<td>OD Area</td>
<td>1.767</td>
<td>inch²</td>
</tr>
<tr>
<td></td>
<td>0.012</td>
<td>ft²</td>
</tr>
<tr>
<td>ID Area</td>
<td>1.287</td>
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<td></td>
<td>0.009</td>
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### CASING

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</tr>
<tr>
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<tr>
<td></td>
<td>0.196</td>
<td>ft²</td>
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### ANNULAR AREA

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<tr>
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<th></th>
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<td>ft²</td>
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<td>inch²</td>
</tr>
<tr>
<td></td>
<td>0.147</td>
<td>ft²</td>
</tr>
<tr>
<td>Test N°</td>
<td>Floco Meter</td>
<td>Liquid Rate</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>1</td>
<td>19.2</td>
<td>449.77</td>
</tr>
<tr>
<td>2</td>
<td>21.1</td>
<td>410.45</td>
</tr>
<tr>
<td>3</td>
<td>20.6</td>
<td>416.42</td>
</tr>
<tr>
<td>4</td>
<td>20.9</td>
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<td>5</td>
<td>36.3</td>
<td>237.79</td>
</tr>
<tr>
<td>6</td>
<td>36.4</td>
<td>237.36</td>
</tr>
<tr>
<td>7</td>
<td>38.1</td>
<td>235.49</td>
</tr>
<tr>
<td>8</td>
<td>36.8</td>
<td>235.10</td>
</tr>
<tr>
<td>9</td>
<td>45.0</td>
<td>132.92</td>
</tr>
</tbody>
</table>

**SEPARATOR TYPE:** Bucket
**OD DIP TUBE=1.5”**
**NUMBER OF SLOTS=1**
**DIMENSIONS OF THE SLOTS= 3” x 6”**
**FLUID ENTERING IN FRONT THE ANCHOR PORTS**
SEPARATOR TYPE: Bucket

OD DIP TUBE = 1.5"
NUMBER OF ANCHOR PORTS = 1
DIMENSIONS OF THE ANCHOR PORTS = 6" x 3"
FLUID ENTERING IN FRONT THE ANCHOR PORTS
Pc = 10 psi

Figure 5-19
As with the Patterson and Echometer models, increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate in separator.

In Figure 5-19, it is noticed that when the liquid velocity is between 11.04 and 12.10 inches/second, the gas rate in separator increases from 0.658 MSCFD to 1.080 MSCFD (liquid curve). When the liquid velocity is 12.10 inches/second and gas velocity is 53.10 inches/second as in Test 1 and the liquid velocity is 11.04 inches/second and gas velocity is 37.14 inches/second as in Test 2, the waterfall phenomenon is observed (Figure 5-12, Tests 1 and 2).

When the liquid velocity is between 6.32 to 6.40 inches/second, the gas rate in separator increases from 0.024 MSCFD (Figure 5-20, Test 8) to 0.425 MSCFD (Figure 5-20, Test 5).

Liquid velocity values for design can be obtained from the zero curve. For example, for designing a separator at gas velocity equal to 57.97 inches/second, the liquid velocity must be 3.58 inches/second (Figure 5-20, Test 9).

**Figure 5-20: Bucket tests (Fluid entering in front the anchor ports at Pc =10 psi)**
Figure 5-20 – continued

Test 3

Test 4

Test 5

Test 6

Test 7

Test 8
Fluid Entering Below the Anchor Ports

Table 5-8 shows the data obtained from the tests and the data calculated for the Bucket model when the fluid is entering below the anchor ports and the casing pressure is 10 psi.
<table>
<thead>
<tr>
<th>Date</th>
<th>09/20/2004</th>
</tr>
</thead>
</table>

## Table 5-8

**SEPARATOR TYPE:** Bucket

**OD DIP TUBE:** 1.5"  
**NUMBER OF SLOTS:** 1  
**DIMENSIONS OF THE SLOTS:** 3" x 6"  
**FLUID ENTERING BELOW THE ANCHOR PORTS**

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Place Meter</th>
<th>Liquid Rate</th>
<th>Gas meter reading</th>
<th>Gas Rate SCFM</th>
<th>Gas Rate MCF</th>
<th>Annulus Pressure Maximum</th>
<th>Annulus Pressure Minimum</th>
<th>Ports Pressure Maximum</th>
<th>Ports Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Tubing Pressure Minimum</th>
<th><em>Liquid</em> Velocity in Separator</th>
<th><em>Gas</em> Velocity in Casing</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.7</td>
<td>469.24</td>
<td>95%</td>
<td>14.78</td>
<td>108.66</td>
<td>110.26</td>
<td>12.2</td>
<td>11.5</td>
<td>10.5</td>
<td>8.7</td>
<td>7.3</td>
<td>13.16</td>
<td>2.59</td>
<td>51.50</td>
<td>1.10</td>
<td>10.00</td>
<td>1.5888</td>
</tr>
<tr>
<td>2</td>
<td>17.8</td>
<td>454.28</td>
<td>86%</td>
<td>9.86</td>
<td>110.30</td>
<td>73.95</td>
<td>12.7</td>
<td>11.8</td>
<td>10.5</td>
<td>8.9</td>
<td>7.8</td>
<td>7.66</td>
<td>2.63</td>
<td>34.57</td>
<td>1.05</td>
<td>1.5133</td>
<td>1.5133</td>
</tr>
<tr>
<td>3</td>
<td>17.4</td>
<td>467.41</td>
<td>15%</td>
<td>1.64</td>
<td>120.88</td>
<td>13.48</td>
<td>11.0</td>
<td>10.5</td>
<td>9.6</td>
<td>8.5</td>
<td>6.4</td>
<td>13.64</td>
<td>2.66</td>
<td>6.77</td>
<td>0.78</td>
<td>1.1281</td>
<td>1.1281</td>
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<tr>
<td>4</td>
<td>18.2</td>
<td>240.87</td>
<td>9%</td>
<td>0.16</td>
<td>105.75</td>
<td>110.24</td>
<td>11.3</td>
<td>10.9</td>
<td>8.9</td>
<td>8.5</td>
<td>7.8</td>
<td>6.44</td>
<td>1.17</td>
<td>34.44</td>
<td>0.82</td>
<td>0.8642</td>
<td>0.8664</td>
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<td>5</td>
<td>36.1</td>
<td>239.27</td>
<td>60%</td>
<td>9.98</td>
<td>111.85</td>
<td>75.23</td>
<td>11.4</td>
<td>10.5</td>
<td>9.4</td>
<td>8.9</td>
<td>7.6</td>
<td>7.04</td>
<td>1.27</td>
<td>36.96</td>
<td>110.00</td>
<td>0.8566</td>
<td>0.8566</td>
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<tr>
<td>6</td>
<td>35.9</td>
<td>241.34</td>
<td>36%</td>
<td>4.93</td>
<td>117.29</td>
<td>39.32</td>
<td>10.5</td>
<td>10.4</td>
<td>8.5</td>
<td>8.5</td>
<td>6.6</td>
<td>6.44</td>
<td>1.28</td>
<td>10.65</td>
<td>78.00</td>
<td>0.4465</td>
<td>0.4465</td>
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<tr>
<td>7</td>
<td>35.8</td>
<td>240.47</td>
<td>10%</td>
<td>1.64</td>
<td>120.76</td>
<td>13.49</td>
<td>10.5</td>
<td>10.0</td>
<td>8.2</td>
<td>7.5</td>
<td>6.2</td>
<td>6.47</td>
<td>1.27</td>
<td>6.86</td>
<td>35.00</td>
<td>0.2095</td>
<td>0.2095</td>
</tr>
<tr>
<td>8</td>
<td>68.5</td>
<td>127.08</td>
<td>90%</td>
<td>14.78</td>
<td>113.89</td>
<td>113.89</td>
<td>10.2</td>
<td>10.2</td>
<td>8.5</td>
<td>8.5</td>
<td>6.6</td>
<td>6.47</td>
<td>0.87</td>
<td>37.17</td>
<td>0.00</td>
<td>0.0050</td>
<td>0.0050</td>
</tr>
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</table>

109
SEPARATOR TYPE: Bucket

OD DIP TUBE = 1.5"
NUMBER OF ANCHOR PORTS = 1
DIMENSIONS OF THE ANCHOR PORTS = 6" x 3"
FLUID ENTERING BELOW THE ANCHOR PORTS
Pc = 10 psi

Figure 5-21

Superficial Gas Velocity in casing annulus (in/sec)
Superficial Liquid Velocity inside Separator (in/sec)

Gas Rate through Separator (MSCF/day)
When the fluid is entering in front and below the perforations, the behavior is almost the same, therefore, increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate in separator. The difference is in the slopes of the curves (liquid and gas curve). The slopes of the liquid and gas curves when the fluid is entering below the perforations are greater than the slopes of the liquid and gas curves when the fluid is entering in front of the perforations.

There is not too much variation between the two first points in the liquid curve for liquid velocities between 13.16 and 13.28 inches/second (Figure 5-21). The gas rates in separator for Test 1 and Test 2 are very similar, 1.584 for Test 1 and 1.512 for Test 2. Figure 5-22 (Tests 1 and 2) shows almost the same gas rate for both tests. Test 1 and Test 2 presents an intermittent “waterfall”, this means that the waterfall is not constant. The variation of gas rate in separator between Test 2 and Test 3 is 0.245 MSCFD, this is corroborated in Figure 5-22 (Tests 2 and 3). As it is noticed in Figure 5-22 (Test 3 and 4), there is not too much variation between Test 3 and Test 4.

The variation between each of the four points on the liquid curve for liquid velocities between 6.44 and 6.49 inches/second (Figure 5-21) averages 0.215 MSCFD. This difference is noticed in Figure 5-21; however, this difference cannot be readily seen in the photographs of Figure 5-22 (Tests 5, 6, 7, and 8).

The optimum design liquid velocity for any gas velocity is less than 3.42 inches/second. Figure 5-22 (Test 9) shows that there is almost not gas entering through the dip tube.
Figure 5-22: Bucket 1 tests (Fluid entering below the anchor ports at $P_c = 10$ psi)
Fluid Entering Above the Anchor Ports

Table 5-9 shows the data obtained from the tests and the data calculated for the Bucket model when the fluid is entering above the anchor ports and the casing pressures are 5 and 10 psi.
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| Test N° | Floco N° | Liquid Rate | Gas meter reading | Gas Rate MCF | Meter Pressure | Gas Rate MSCF | Annulus Pressure Maximum | Annulus Pressure Minimum | Ports Pressure Maximum | Ports Pressure Minimum | Tubing Pressure Maximum | Tubing Pressure Minimum | Superficial Liquid Velocity in Separator | Superficial Liquid Velocity in Casing | Superficial Gas Velocity in Casing | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | FL-3820C | FL-3830ST | FL-35000 SCFM | MCF | Comments |
| 1 | 11.8 | 731.58 | 90% | 14.78 | 109.28 | 90% | 14.78 | 109.28 | 11.0 | 9.0 | 8.0 | 7.0 | 6.0 | 5.0 | 4.0 | 3.0 | 2.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | FLUID ENTERING ABOVE THE ANCHOR PORTS |
| 2 | 11.2 | 744.83 | 90% | 14.78 | 109.28 | 90% | 14.78 | 109.28 | 11.0 | 9.0 | 8.0 | 7.0 | 6.0 | 5.0 | 4.0 | 3.0 | 2.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | FLUID ENTERING ABOVE THE ANCHOR PORTS |

### Table 5-9

**SEPARATOR TYPE:** Bucket

**OD DIP TUBE:** 1.5"

**NUMBER OF SLOTS:** 1

**DIMENSIONS OF THE SLOTS:** 3" x 6"

**FLUID ENTERING ABOVE THE ANCHOR PORTS**
Figure 5-23 shows pictures of the dip tube of the Bucket model when the fluid is entering above the anchor ports. It is observed that there is almost no gas entering the dip tube.

These tests were made with two different casing pressures, one at 5 psi (Figure 5-23, Test 1) and the other at 10 psi (Figure 5-23, Test 2).

The liquid and gas rates used for these tests were the maximum to analyze the worst-case scenario, therefore, if in the worst case the gas rate through separator is almost zero, it is not necessary to conduct more tests at lower gas or liquid rates.
5.1.6 Analysis of the effect of the Position of the Anchor Ports Relative to the Perforations on the performance of the Bucket Separator

Similar to Patterson and Echometer models, when the fluid is entering above the anchor ports, the volume of gas entering the downhole gas separator is zero and it is only necessary to have one foot between the anchor ports and the perforations to obtain this effect.

When the fluid is entering in front of the anchor ports, the maximum volume of gas rate entering the downhole gas separator is 1.08 MSCFD while the gas injected into the well is 107.89 MSCFD (gas velocity = 53.10 inches/second) and the liquid rate is 449.77 BBD (liquid velocity = 12.10 inches/second).

The maximum gas rate entering the downhole gas separator is 1.584 MSCFD (fluid is entering below the anchor ports), when the gas rate injected into the well is 109.28 MSCFD (gas velocity = 51.50 inches/second) and the liquid rate is 489.24 BBD (liquid velocity = 13.16 inches/second).

5.1.7 Comparative analysis of all downhole gas separator models

For all the downhole gas separators tested in this project (Patterson, Echometer and Bucket models), when the fluid is entering above the anchor ports, the volume of gas entering the downhole gas separator is practically zero. The distance from the anchor ports and the perforations only needs to be a foot. This behavior is not exclusive to the downhole gas separators tested in this project. Any downhole gas separator that is placed in the position that the anchor ports are least one foot from the last perforations will not have much gas entering through the separator.

When the fluid is entering in front of the anchor ports, the downhole gas separator with the best behavior is Patterson 2. Bucket has the worst behavior at this position.
Figure 5-24

PATTERSON 2 vs ECHOMETER 1 vs BUCKET
FLUID ENTERING IN FRONT THE SLOTS @ 10 psi
In the oil industry, the optimal liquid velocity used for designing a downhole gas separator is 6 inches/second. In Figure 5-24, for any gas velocity with a liquid velocity less than 6 inches/second, there is no gas entering the downhole gas separator for Patterson 2 and Echometer 1, but, for Bucket, the optimal liquid velocity is 4 inches/second.

The most critical position for all the models is when the fluid is entering below the anchor ports since this is the most common position for the gas separator in the real world. At this position, Echometer 1 and Patterson 2 have almost the same behavior. Bucket has the worst behavior—in some cases almost two times the gas rate going through the downhole gas separator in comparison with Patterson 2 and Echometer 1.

In Figure 5-25, for any gas rate, with a liquid velocity equal to 3 inches/second, there is no gas entering the downhole gas separator for any of the three separator models. This liquid velocity value would be optimal for a conservative design.
Figure 5-25

PATTERSON 2 vs ECHOMETER 1 vs BUCKET
FLUID ENTERING BELOW THE SLOTS @ 10 psi
5.2 Effect of Anchor Port Width on Separator Efficiency

The effect of separator anchor port width was studied in this project for the Patterson models by increasing the anchor port width while keeping constant the length and location of the anchor ports:

- Patterson 1 => anchor ports = 8” x 1/8” & dip tube = 1”
- Patterson 2 => anchor ports = 8” x 1/4” & dip tube = 1”
- Patterson 3 => anchor ports = 8” x 1/2” & dip tube = 1”
- Patterson 4 => anchor ports = 8” x 3/4” & dip tube = 1”

In this chapter, tables will be presented with the measured and calculated data for each Patterson model described above.

5.2.1 Geometry of Separators

5.2.1.1 Patterson 1 separator

Figure 5-26 (5-26a and 5-26b) shows the Patterson 1 model. It is observed in the pictures that Patterson 1 has eight anchor ports distributed in two rows. Each anchor port is 8 inches long and 1/8 inches wide. The dip tube is 1 inch OD and 3/4 inches ID. The characteristics of the geometry of this separator are detailed in Figure 5-27.
### Geometry of Patterson 1

#### GAS ANCHOR

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<thead>
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<th>Value</th>
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</thead>
<tbody>
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<tr>
<td>ID</td>
<td>2.750 inches</td>
</tr>
<tr>
<td>OD Area</td>
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#### HOLES

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<td>0.001 ft^2</td>
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<tr>
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<td>0.005 ft^2</td>
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#### SLOTS

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<td>Longitude</td>
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</tr>
<tr>
<td>Width</td>
<td>0.125 inches</td>
</tr>
<tr>
<td>Area of each slot</td>
<td>1.000 inch^2</td>
</tr>
<tr>
<td></td>
<td>0.007 ft^2</td>
</tr>
<tr>
<td>Total Area</td>
<td>8.000 inch^2</td>
</tr>
<tr>
<td></td>
<td>0.056 ft^2</td>
</tr>
</tbody>
</table>

#### DIP TUBE INSIDE THE ANCHOR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD</td>
<td>1.000 inches</td>
</tr>
<tr>
<td>ID</td>
<td>0.750 inches</td>
</tr>
<tr>
<td>OD Area</td>
<td>0.785 inch^2</td>
</tr>
<tr>
<td></td>
<td>0.005 ft^2</td>
</tr>
<tr>
<td>ID Area</td>
<td>0.442 inch^2</td>
</tr>
<tr>
<td></td>
<td>0.003 ft^2</td>
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</table>

#### CASING

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>6.000 inches</td>
</tr>
<tr>
<td>ID Area</td>
<td>28.274 inch^2</td>
</tr>
<tr>
<td></td>
<td>0.196 ft^2</td>
</tr>
</tbody>
</table>

#### ANNULAR AREA

<table>
<thead>
<tr>
<th>Layer</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchor/Dip Tube</td>
<td>5.154 inch^2</td>
</tr>
<tr>
<td></td>
<td>0.036 ft^2</td>
</tr>
<tr>
<td>Casing-Anchor</td>
<td>21.206 inch^2</td>
</tr>
<tr>
<td></td>
<td>0.147 ft^2</td>
</tr>
</tbody>
</table>
5.2.1.2 Patterson 2 (5.1.1)

The geometry of this separator model was discussed in detail in section 5.1.1.

5.2.1.3 Patterson 3

Figure 5-28 (5-28a and 5-28b) shows the Patterson 3 model. It is observed in the pictures that Patterson 1 has eight anchor ports. Each anchor port is 8 inches long and 1/2 inches wide. The dip tube is 1 inch OD and 3/4 inches ID. The characteristics of the geometry of this separator are detailed in Figure 5-29.

Figure 5-28: Patterson 3
### Figure 5-29: Geometry of Patterson 3

#### GAS ANCHOR

<p>| | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>OD</td>
<td>3.000</td>
<td>inches</td>
</tr>
<tr>
<td>ID</td>
<td>2.750</td>
<td>inches</td>
</tr>
<tr>
<td>OD Area</td>
<td>7.069</td>
<td>inch^2</td>
</tr>
<tr>
<td></td>
<td>0.049</td>
<td>ft^2</td>
</tr>
<tr>
<td>ID Area</td>
<td>5.940</td>
<td>inch^2</td>
</tr>
<tr>
<td></td>
<td>0.041</td>
<td>ft^2</td>
</tr>
</tbody>
</table>

#### HOLES

<p>| | | |</p>
<table>
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<th></th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td>ID</td>
<td>0.500</td>
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</tr>
<tr>
<td>Area of each hole</td>
<td>0.196</td>
<td>inch^2</td>
</tr>
<tr>
<td></td>
<td>0.001</td>
<td>ft^2</td>
</tr>
<tr>
<td>Total Area</td>
<td>0.785</td>
<td>inch^2</td>
</tr>
<tr>
<td></td>
<td>0.005</td>
<td>ft^2</td>
</tr>
</tbody>
</table>

#### SLOTS

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</thead>
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<td>Number of holes</td>
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</tr>
<tr>
<td>Longitude</td>
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</tr>
<tr>
<td>Width</td>
<td>0.500</td>
<td>inches</td>
</tr>
<tr>
<td>Area of each slot</td>
<td>4.000</td>
<td>inch^2</td>
</tr>
<tr>
<td></td>
<td>0.028</td>
<td>ft^2</td>
</tr>
<tr>
<td>Total Area</td>
<td>32.000</td>
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</tr>
<tr>
<td></td>
<td>0.222</td>
<td>ft^2</td>
</tr>
</tbody>
</table>

#### DIP TUBE INSIDE THE ANCHOR

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>OD</td>
<td>1.000</td>
<td>inches</td>
</tr>
<tr>
<td>ID</td>
<td>0.750</td>
<td>inches</td>
</tr>
<tr>
<td>OD Area</td>
<td>0.785</td>
<td>inch^2</td>
</tr>
<tr>
<td></td>
<td>0.005</td>
<td>ft^2</td>
</tr>
<tr>
<td>ID Area</td>
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<td>inch^2</td>
</tr>
<tr>
<td></td>
<td>0.003</td>
<td>ft^2</td>
</tr>
</tbody>
</table>

#### CASING

<p>| | | |</p>
<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>6.000</td>
<td>inches</td>
</tr>
<tr>
<td>ID Area</td>
<td>28.274</td>
<td>inch^2</td>
</tr>
<tr>
<td></td>
<td>0.196</td>
<td>ft^2</td>
</tr>
</tbody>
</table>

#### ANNULAR AREA

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchor/Dip Tube</td>
<td>5.154</td>
<td>inch^2</td>
</tr>
<tr>
<td></td>
<td>0.036</td>
<td>ft^2</td>
</tr>
<tr>
<td>Casing-Anchor</td>
<td>21.206</td>
<td>inch^2</td>
</tr>
<tr>
<td></td>
<td>0.147</td>
<td>ft^2</td>
</tr>
</tbody>
</table>
5.2.1.4 Patterson 4

Figure 5-30 (5-30a and 5-30b) shows the Patterson 4 model. It is observed in the pictures that Patterson 1 has eight anchor ports. Each anchor port is 8 inches long and 3/4 inches wide. The dip tube is 1 inch OD and 3/4 inches ID. The characteristics of the geometry of this separator are detailed in Figure 5-31.

Figure 5-30 Patterson 4

5.2.2 Tests

A. Anchor ports located in front the perforations

Patterson 1

Table 5-10 shows the data obtained from the test and the data calculated for Patterson 1 when the fluid is entering the wellbore through perforations located in front the anchor ports and the casing pressure is 10 psi.
**Figure 5-31: Geometry of Patterson 4**

<table>
<thead>
<tr>
<th>GAS ANCHOR</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>OD</td>
<td>3.000</td>
<td>inches</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID</td>
<td>2.750</td>
<td>inches</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OD Area</td>
<td>7.069</td>
<td>inch(^2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID Area</td>
<td>5.940</td>
<td>inch(^2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| HOLEs               |            |            |            |            |            |            |            |            |            |
| Number of holes     | 4.000      |            |            |            |            |            |            |            |            |
| ID                  | 0.500      | inches     |            |            |            |            |            |            |            |
| Area of each hole   | 0.196      | inch\(^2\) |            |            |            |            |            |            |            |
| Total Area          | 0.785      | inch\(^2\) |            |            |            |            |            |            |            |

| SLOTS               |            |            |            |            |            |            |            |            |            |
| Number of holes     | 8.000      |            |            |            |            |            |            |            |            |
| Longitude           | 8.000      | inches     |            |            |            |            |            |            |            |
| Width               | 0.750      | inches     |            |            |            |            |            |            |            |
| Area of each slot   | 6.000      | inch\(^2\) |            |            |            |            |            |            |            |
| Total Area          | 48.000     | inch\(^2\) |            |            |            |            |            |            |            |

| DIP TUBE INSIDE THE ANCHOR |            |            |            |            |            |            |            |            |            |
| OD                  | 1.000      | inches     |            |            |            |            |            |            |            |
| ID                  | 0.750      | inches     |            |            |            |            |            |            |            |
| OD Area             | 0.785      | inch\(^2\) |            |            |            |            |            |            |            |
| ID Area             | 0.442      | inch\(^2\) |            |            |            |            |            |            |            |

| CASING              |            |            |            |            |            |            |            |            |            |
| ID                  | 6.000      | inches     |            |            |            |            |            |            |            |
| ID Area             | 28.274     | inch\(^2\) |            |            |            |            |            |            |            |

| ANNULAR AREA        |            |            |            |            |            |            |            |            |            |
| Anchor/Dip Tube     | 5.154      | inch\(^2\) |            |            |            |            |            |            |            |
| Casing-Anchor       | 21.206     | inch\(^2\) |            |            |            |            |            |            |            |

|            |            |            |            |            |            |            |            |            |            |

**125**
### Table 5-10

**SEPARATOR TYPE:** Patterson 1  
**OD DIP TUBE= 1”**  
**NUMBER OF SLOTS=8**  
**DIMENSIONS OF THE SLOTS=8” x 1/8”**  
**FLUID ENTERING IN FRONT THE ANCHOR PORTS**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Floco Meter</th>
<th>Liquid Rate</th>
<th>Gas Rate</th>
<th>Gas Rate MCF</th>
<th>Gas Rate Meter</th>
<th>Gas Rate Pressure</th>
<th>Annulus Pressure Maximum</th>
<th>Annulus Pressure Minimum</th>
<th>Ports Pressure Maximum</th>
<th>Ports Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Tubing Pressure Minimum</th>
<th>Super. Liquid Velocity in Separator</th>
<th>Super. Gas Velocity in Casing</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.6</td>
<td>685.17</td>
<td>14.78</td>
<td>109.15</td>
<td>90%</td>
<td>75.17</td>
<td>11.0</td>
<td>10.0</td>
<td>11.0</td>
<td>10.0</td>
<td>11.0</td>
<td>9.86</td>
<td>3.8</td>
<td>3.63</td>
<td>54.89</td>
<td>40</td>
<td>0.239</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>12.6</td>
<td>685.17</td>
<td>90%</td>
<td>75.17</td>
<td>60%</td>
<td>112.10</td>
<td>11.0</td>
<td>10.0</td>
<td>11.0</td>
<td>10.0</td>
<td>11.0</td>
<td>9.86</td>
<td>3.8</td>
<td>3.63</td>
<td>37.79</td>
<td>35</td>
<td>0.209</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>12.6</td>
<td>685.17</td>
<td>30%</td>
<td>117.48</td>
<td>30%</td>
<td>75.17</td>
<td>11.0</td>
<td>10.0</td>
<td>11.0</td>
<td>10.0</td>
<td>11.0</td>
<td>9.86</td>
<td>3.8</td>
<td>3.63</td>
<td>19.63</td>
<td>25</td>
<td>0.156</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>12.6</td>
<td>685.17</td>
<td>10%</td>
<td>13.40</td>
<td>10%</td>
<td>120.42</td>
<td>10.8</td>
<td>10.0</td>
<td>11.0</td>
<td>10.0</td>
<td>11.0</td>
<td>9.86</td>
<td>3.8</td>
<td>3.63</td>
<td>6.75</td>
<td>20</td>
<td>0.120</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>15.8</td>
<td>546.84</td>
<td>90%</td>
<td>118.40</td>
<td>90%</td>
<td>118.40</td>
<td>11.0</td>
<td>10.0</td>
<td>11.0</td>
<td>10.0</td>
<td>11.0</td>
<td>9.86</td>
<td>3.8</td>
<td>3.63</td>
<td>59.42</td>
<td>17</td>
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<td>273.42</td>
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<td>90%</td>
<td>118.40</td>
<td>11.0</td>
<td>10.0</td>
<td>11.0</td>
<td>10.0</td>
<td>11.0</td>
<td>9.86</td>
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<td>3.63</td>
<td>60.31</td>
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</tr>
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</table>
SEPARATOR TYPE: Patterson 1

OD DIP TUBE = 1"
NUMBER OF ANCHOR PORTS = 8
DIMENSIONS OF THE ANCHOR PORTS = 8" x 1/8"
FLUID ENTERING IN FRONT THE ANCHOR PORTS
Pc = 10 psi

Figure 5-32

Gas Rate through Separator (MSCF/day)

Superficial Liquid Velocity inside Separator (in/sec)

Superficial Gas Velocity in casing annulus (in/sec)
Increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate flowing through the separator. In Figure 5-32, it is noticed that when the liquid velocity is between 11.92 and 14.94 inches/second, the gas rate in separator increases from 0.102 MSCFD to 0.239 MSCFD (liquid trend curve). Figure 5-33 (Tests 1, 2, 3, 4 and 5) shows this variation of the gas rate in separator.

When the liquid velocity is 5.96 inches/second and the gas velocity is 60.31 inches/second, the gas rate in separator is zero (Figure 5-28, Test 6).

**Figure 5-33: Patterson 1 tests (Fluid entering in front the anchor ports at Pc =10 psi)**
Test 5

Test 6

Patterson 2

Table 5-1 shows the data obtained from the test and the data calculated for Patterson 2 when the fluid is entering the wellbore through perforations located in front the anchor ports and the casing pressure is 10 psi.

Patterson 3

Table 5-11 shows the data obtained from the test and the data calculated for Patterson 3 when the fluid is entering the wellbore through perforations located in front the anchor ports and the casing pressure is 10 psi.
<table>
<thead>
<tr>
<th>Test N°</th>
<th>Floco Meter</th>
<th>Liquid Rate</th>
<th>Gas meter Reading</th>
<th>Gas Rate MCF</th>
<th>Gas Rate MSCF</th>
<th>Annulus Pressure Maximum</th>
<th>Annulus Pressure Minimum</th>
<th>Ports Pressure Maximum</th>
<th>Ports Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Tubing Pressure Minimum</th>
<th>Superficial Liquid Velocity in Separator</th>
<th>Superficial Gas Velocity in Casing</th>
<th>Superficial Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.5</td>
<td>692.31</td>
<td>90% 14.78</td>
<td>99.79</td>
<td>100.33</td>
<td>10.5</td>
<td>9.5</td>
<td>8.5</td>
<td>7.0</td>
<td>3.0</td>
<td>2.5</td>
<td>15.09</td>
<td>3.67</td>
<td>51.55</td>
<td>115</td>
<td>0.049</td>
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<tr>
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<td>684.09</td>
<td>60% 9.86</td>
<td>101.68</td>
<td>68.16</td>
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<td>9.5</td>
<td>8.5</td>
<td>7.5</td>
<td>3.0</td>
<td>3.0</td>
<td>14.91</td>
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<td>35.02</td>
<td>90</td>
<td>0.039</td>
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<tr>
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<td>12.0</td>
<td>688.45</td>
<td>30% 4.93</td>
<td>100.24</td>
<td>36.61</td>
<td>10.5</td>
<td>9.5</td>
<td>8.0</td>
<td>7.5</td>
<td>3.0</td>
<td>3.0</td>
<td>15.01</td>
<td>3.65</td>
<td>18.30</td>
<td>78</td>
<td>0.034</td>
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</tr>
<tr>
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<td>567.67</td>
<td>90% 14.78</td>
<td>101.05</td>
<td>101.62</td>
<td>10.5</td>
<td>9.5</td>
<td>8.0</td>
<td>7.0</td>
<td>4.0</td>
<td>3.5</td>
<td>12.38</td>
<td>3.0</td>
<td>52.22</td>
<td>60</td>
<td>0.028</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>15.2</td>
<td>568.16</td>
<td>60% 9.86</td>
<td>102.81</td>
<td>68.78</td>
<td>10.5</td>
<td>9.5</td>
<td>8.5</td>
<td>7.5</td>
<td>4.2</td>
<td>4.0</td>
<td>12.17</td>
<td>2.96</td>
<td>35.38</td>
<td>45</td>
<td>0.070</td>
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<td>548.57</td>
<td>30% 4.93</td>
<td>107.02</td>
<td>36.04</td>
<td>10.5</td>
<td>9.5</td>
<td>8.5</td>
<td>7.5</td>
<td>4.5</td>
<td>4.2</td>
<td>11.96</td>
<td>2.91</td>
<td>18.54</td>
<td>36</td>
<td>0.017</td>
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</tr>
<tr>
<td>7</td>
<td>20.6</td>
<td>280.52</td>
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<td>102.52</td>
<td>103.12</td>
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<td>10.0</td>
<td>8.0</td>
<td>7.5</td>
<td>6.0</td>
<td>6.0</td>
<td>6.12</td>
<td>1.49</td>
<td>51.84</td>
<td>0</td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-11

SEPARATOR TYPE: Patterson 3
OD DIP TUBE= 1"
NUMBER OF SLOTS=8
DIMENSIONS OF THE SLOTS=8” x 1/2”
FLUID ENTERING IN FRONT THE ANCHOR PORTS

<table>
<thead>
<tr>
<th>Date</th>
<th>6/30/2004</th>
</tr>
</thead>
</table>

DIMENSIONS OF THE SLOTS=8” x 1/2”
SEPARATOR TYPE: Patterson 3

OD DIP TUBE = 1"
NUMBER OF ANCHOR PORTS = 8
DIMENSIONS OF THE ANCHOR PORTS = 8" x 1/2"
FLUID ENTERING IN FRONT THE ANCHOR PORTS
Pc = 10 psi

Figure 5-34

Supercritical Liquid Velocity inside Separator (in/sec)
Supercritical Gas Velocity in casing annulus (in/sec)
Gas Rate through Separator (MSCF/day)
In Figure 5-34, it is noticed that when the liquid velocity is between 14.91 and 15.09 inches/second, the gas rate in separator increases from 0.034 MSCFD to 0.049 MSCFD (liquid trend curve). Figure 5-35 (Tests 1, 2 and 3) shows this small variation of the gas rate in separator. It is observed, when the liquid velocity is between 11.96 and 12.38 inches/second that the gas rate in separator increases from 0.017 MSCFD to 0.026 MSCFD (liquid trend curve). Figure 5-35 (Tests 4, 5 and 6) shows this very small variation of the gas rate in separator.

When the liquid velocity is 6.12 inches/second and the gas velocity is 51.84 inches/second, the gas rate in separator is zero (Figure 5-35, Test 7).

Figure 5-35: Patterson 3 tests (Fluid entering in front the anchor ports at Pc =10 psi)
Table 5-12 shows the data obtained from the test and the data calculated for Patterson 4 when the fluid is entering the wellbore through perforations located in front the anchor ports and the casing pressure is 10 psi.
### Table 5-12

**SEPARATOR TYPE: Patterson 4**  
**OD DIP TUBE= 1”**  
**DIMENSIONS OF THE SLOTS=8” x 3/4”**  
**FLUID ENTERING IN FRONT THE ANCHOR PORTS**

<table>
<thead>
<tr>
<th>Test No</th>
<th>Floco Meter</th>
<th>Liquid Rate</th>
<th>Gas Rate Meter Reading</th>
<th>Gas Rate MCF</th>
<th>Gas Rate Pressure</th>
<th>Annulus Pressure Maximum</th>
<th>Annulus Pressure Minimum</th>
<th>Ports Pressure Maximum</th>
<th>Ports Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Tubing Pressure Minimum</th>
<th>Superficial Liquid Velocity in Separator</th>
<th>Superficial Gas Velocity in Casing</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.5</td>
<td>690.66</td>
<td>90%</td>
<td>14.78</td>
<td>109.70</td>
<td>110.32</td>
<td>11.0</td>
<td>10.0</td>
<td>8.2</td>
<td>7.5</td>
<td>3.0</td>
<td>3.5</td>
<td>15.06</td>
<td>3.66</td>
<td>55.47</td>
<td>105</td>
<td>0.040</td>
</tr>
<tr>
<td>2</td>
<td>12.2</td>
<td>705.88</td>
<td>60%</td>
<td>9.88</td>
<td>84.86</td>
<td>86.87</td>
<td>11.1</td>
<td>10.1</td>
<td>8.2</td>
<td>7.5</td>
<td>3.5</td>
<td>2.8</td>
<td>15.39</td>
<td>3.74</td>
<td>38.53</td>
<td>99</td>
<td>0.042</td>
</tr>
<tr>
<td>3</td>
<td>12.3</td>
<td>702.44</td>
<td>30%</td>
<td>4.93</td>
<td>118.95</td>
<td>119.87</td>
<td>11.0</td>
<td>10.4</td>
<td>8.1</td>
<td>7.6</td>
<td>2.8</td>
<td>2.6</td>
<td>15.31</td>
<td>3.72</td>
<td>19.89</td>
<td>73</td>
<td>0.032</td>
</tr>
<tr>
<td>4</td>
<td>15.2</td>
<td>585.42</td>
<td>90%</td>
<td>14.79</td>
<td>111.77</td>
<td>121.40</td>
<td>11.5</td>
<td>10.2</td>
<td>8.5</td>
<td>7.5</td>
<td>4.3</td>
<td>4.2</td>
<td>12.39</td>
<td>3.01</td>
<td>55.47</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>5</td>
<td>31.2</td>
<td>277.01</td>
<td>90%</td>
<td>14.78</td>
<td>110.15</td>
<td>110.73</td>
<td>11.0</td>
<td>10.0</td>
<td>7.5</td>
<td>7.0</td>
<td>5.0</td>
<td>4.5</td>
<td>6.04</td>
<td>1.47</td>
<td>55.09</td>
<td>0</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**DIMENSIONS OF THE SLOTS=8” x 3/4”**
SEPARATOR TYPE: Patterson 4

OD DIP TUBE = 1"
NUMBER OF ANCHOR PORTS = 8
DIMENSIONS OF THE ANCHOR PORTS = 8" x 3/4"
FLUID ENTERING IN FRONT THE ANCHOR PORTS
Pc = 10 psi

Figure 5-36
In Figure 5-36, it is noticed that when the liquid velocity is between 15.06 and 15.39 inches/second, the gas rate in separator increases from 0.032 MSCFD to 0.045 MSCFD (liquid trend curve). Figure 5-37 (Tests 1, 2 and 3) shows this small variation of the gas rate in separator. When the liquid velocity is 12.39 inches/second and the gas velocity is 55.67 inches/second, the gas rate in separator is almost zero (Figure 5-37, Test 4).

When the liquid velocity is 6.04 inches/second and the gas velocity is 55.09 inches/second, the gas rate in separator is zero (Figure 5-37, Test 5).

**Figure 5-37: Patterson 4 tests (Fluid entering in front the anchor ports at Pc = 10 psi)**
B. Anchor Ports Located above the Perforations

Patterson 1

Table 5-13 shows the data obtained from the tests and the data calculated for Patterson 1 when the fluid is entering below the anchor ports and the casing pressure is 10 psi.
# Table 5-13

**SEPARATOR TYPE:** Patterson 1  
**OD DIP TUBE:** 1”  
**NUMBER OF SLOTS:** 8” x 1/8”  
**FLUID ENTERING BELOW THE ANCHOR PORTS**

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Flocculator</th>
<th>Liquid Rate</th>
<th>Gas Rate</th>
<th>Gas Rate CF</th>
<th>Gas Rate MSCF</th>
<th>Annulus Pressure Maximum</th>
<th>Annulus Pressure Minimum</th>
<th>Ports Pressure Maximum</th>
<th>Ports Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Tubing Pressure Minimum</th>
<th>Superficial Liquid Velocity in Separator</th>
<th>Superficial Liquid Velocity in Casing</th>
<th>Superficial Gas Velocity in Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>15.6</td>
<td>552.43</td>
<td>96%</td>
<td>14.13</td>
<td>107.41</td>
<td>106.56</td>
<td>10.5</td>
<td>9.5</td>
<td>2.0</td>
<td>12.04</td>
<td>2.93</td>
<td>55.79</td>
<td>105</td>
<td>0.628</td>
<td>WATERFALL FLOW</td>
<td>0.1BBl</td>
<td>0.1BBl</td>
<td>0.1BBl</td>
<td>0.1BBl</td>
</tr>
<tr>
<td>2</td>
<td>15.1</td>
<td>571.81</td>
<td>60%</td>
<td>9.86</td>
<td>112.69</td>
<td>75.75</td>
<td>11.0</td>
<td>9.5</td>
<td>2.6</td>
<td>12.47</td>
<td>3.03</td>
<td>38.50</td>
<td>&gt;150</td>
<td>0.65</td>
<td>0.936</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>15.6</td>
<td>553.49</td>
<td>30%</td>
<td>4.93</td>
<td>117.05</td>
<td>39.44</td>
<td>10.5</td>
<td>9.5</td>
<td>2.6</td>
<td>12.07</td>
<td>2.93</td>
<td>20.27</td>
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<td>0.724</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>15.7</td>
<td>549.27</td>
<td>10%</td>
<td>1.64</td>
<td>119.00</td>
<td>13.40</td>
<td>10.5</td>
<td>9.5</td>
<td>3.8</td>
<td>11.97</td>
<td>2.91</td>
<td>8.84</td>
<td>102</td>
<td>0.610</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>31.4</td>
<td>274.99</td>
<td>50%</td>
<td>14.70</td>
<td>117.96</td>
<td>118.25</td>
<td>10.5</td>
<td>9.5</td>
<td>5.8</td>
<td>5.95</td>
<td>1.44</td>
<td>40.75</td>
<td>0</td>
<td>0</td>
<td>0.005</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>31.3</td>
<td>278.30</td>
<td>60%</td>
<td>9.86</td>
<td>113.85</td>
<td>78.35</td>
<td>10.0</td>
<td>9.5</td>
<td>5.0</td>
<td>9.02</td>
<td>1.44</td>
<td>40.15</td>
<td>0</td>
<td>0</td>
<td>0.005</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SEPARATOR TYPE: Patterson 1

OD DIP TUBE = 1"
NUMBER OF ANCHOR PORTS = 8
DIMENSIONS OF THE ANCHOR PORTS = 8" x 1/8"
FLUID ENTERING BELOW THE ANCHOR PORTS
Pc = 10 psi

Figure 5-38
Increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate flowing through the separator.

In Figure 5-38, it is noticed that when the liquid velocity is between 11.97 and 12.47 inches/second, the gas rate in separator increases from 0.610 MSCFD to 0.936 MSCFD (liquid trend curve). Figure 5-39 (Tests 2, 3, and 4) shows this variation of the gas rate in separator.

Something that is very peculiar is that the gas rate in separator for Test 1 (liquid velocity = 12.04 inches/second and gas velocity = 55.79 inches/second) is 0.628 MSCFD. But, Figure 5-39 (Tests 1) shows the waterfall phenomenon at this point. When the waterfall phenomenon is shown, the gas rate in separator is always high; the values are close to 1.0 MSCFD. Therefore, this value represents an error in measurement.

In using the conventionally accepted value of less than or equal to 6 inches/second as design criterion for liquid velocity in the separator, the gas velocity can be any value.

**Figure 5-39: Patterson 1 tests (Fluid entering below the anchor ports at Pc =10 psi)**
Patterson 2

Table 5-2 shows the data obtained from the tests and the data calculated for Patterson 2 when the fluid is entering below the anchor ports and the casing pressure is 10 psi.

Patterson 3

Table 5-13 shows the data obtained from the tests and the data calculated for Patterson 3 when the fluid is entering below the anchor ports and the casing pressure is 10 psi.
<table>
<thead>
<tr>
<th>Test N°</th>
<th>Floco Meter</th>
<th>Liquid Rate</th>
<th>Gas Rate MCF</th>
<th>Meter Pressure Gas</th>
<th>Gas Rate MCF</th>
<th>Inlet Annulus Pressure</th>
<th>Port Pressure Minimum</th>
<th>Tubing Pressure Minimum</th>
<th>Superficial Liquid Velocity in Separator</th>
<th>Superficial Gas Velocity in Casing</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.9</td>
<td>542.71</td>
<td>90%</td>
<td>14.78</td>
<td>109.78</td>
<td>110.40</td>
<td>12.5</td>
<td>11.5</td>
<td>9.8</td>
<td>4.5</td>
<td>4.6</td>
<td>11.83</td>
<td>2.88</td>
<td>&gt;150</td>
</tr>
<tr>
<td>2</td>
<td>16.2</td>
<td>532.35</td>
<td>60%</td>
<td>9.86</td>
<td>113.85</td>
<td>76.33</td>
<td>11.5</td>
<td>10.2</td>
<td>8.5</td>
<td>3.9</td>
<td>3.9</td>
<td>11.61</td>
<td>2.92</td>
<td>&gt;150</td>
</tr>
<tr>
<td>3</td>
<td>15.9</td>
<td>542.71</td>
<td>30%</td>
<td>4.93</td>
<td>118.77</td>
<td>39.81</td>
<td>10.5</td>
<td>9.8</td>
<td>8.5</td>
<td>4.0</td>
<td>4.0</td>
<td>11.83</td>
<td>2.88</td>
<td>120</td>
</tr>
<tr>
<td>4</td>
<td>15.1</td>
<td>527.81</td>
<td>10%</td>
<td>1.64</td>
<td>121.37</td>
<td>13.56</td>
<td>10.0</td>
<td>7.9</td>
<td>7.3</td>
<td>4.0</td>
<td>4.0</td>
<td>12.47</td>
<td>9.0</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>31.4</td>
<td>274.81</td>
<td>90%</td>
<td>14.78</td>
<td>110.41</td>
<td>111.10</td>
<td>10.3</td>
<td>9.8</td>
<td>8.0</td>
<td>5.8</td>
<td>5.8</td>
<td>5.96</td>
<td>4.4</td>
<td>55.61</td>
</tr>
<tr>
<td>6</td>
<td>31.2</td>
<td>276.57</td>
<td>60%</td>
<td>9.86</td>
<td>113.76</td>
<td>76.27</td>
<td>10.5</td>
<td>9.5</td>
<td>8.5</td>
<td>5.5</td>
<td>5.5</td>
<td>6.02</td>
<td>1.47</td>
<td>39.15</td>
</tr>
<tr>
<td>7</td>
<td>31.1</td>
<td>275.17</td>
<td>30%</td>
<td>4.93</td>
<td>118.34</td>
<td>39.67</td>
<td>10.4</td>
<td>10.0</td>
<td>9.0</td>
<td>6.4</td>
<td>6.4</td>
<td>6.06</td>
<td>1.47</td>
<td>20.03</td>
</tr>
<tr>
<td>8</td>
<td>60.0</td>
<td>142.08</td>
<td>90%</td>
<td>14.78</td>
<td>110.13</td>
<td>110.73</td>
<td>11.0</td>
<td>10.0</td>
<td>9.0</td>
<td>6.0</td>
<td>6.0</td>
<td>3.16</td>
<td>0.70</td>
<td>55.66</td>
</tr>
</tbody>
</table>

**Table 5-14**

**SEPARATOR TYPE**: Patterson 3

**OD DIP TUBE**: 1"

**NUMBER OF SLOTS**: 8

**DIMENSIONS OF THE SLOTS**: 8" x 1/2"

**FLUID ENTERING BELOW THE ANCHOR PORTS**
SEPARATOR TYPE: Patterson 3

OD DIP TUBE = 1"
NUMBER OF ANCHOR PORTS = 8
DIMENSIONS OF THE ANCHOR PORTS = 8" x 1/2"
FLUID ENTERING BELOW THE ANCHOR PORTS
Pc = 10 psi

Figure 5-40
Increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate flowing through the separator.

In Figure 5-40, it is noticed that when the liquid velocity is between 11.61 and 12.47 inches/second, the gas rate in separator increases from 0.538 MSCFD to 0.900 MSCFD (liquid trend curve). Figure 5-41 (Tests 1, 2, 3 and 4) shows this variation of the gas rate in separator. It is observed, when the liquid velocity is between 5.99 and 6.06 inches/second, that the gas rate in separator increases from 0.026 MSCFD to 0.419 MSCFD (liquid trend curve). Figure 5-41 (Tests 5, 6 and 7) does not show these differences very clearly. The waterfall phenomenon was observed in Tests 1 and 2 (Figure 5-41).

Liquid velocity values for design can be obtained from the zero curve. For example, for designing a separator at gas velocity equal to 55.68 inches/second, the liquid velocity must be less than 3.10 inches/second (Figure 5-41, Test 8).

**Figure 5-41: Patterson 3 tests (Fluid entering below the anchor ports at Pc =10 psi)**
Figure 5-41-continued

Test 3

Test 4

Test 5

Test 6

Test 7

Test 8
Patterson 4

Table 5-15 shows the data obtained from the tests and the data calculated for Patterson 4 when the fluid is entering below the anchor ports and the casing pressure is 10 psi.

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Flow Meter</th>
<th>Liquid Rate</th>
<th>Gas Rate</th>
<th>Gas Rate Through Separator</th>
<th>Gas Rate Through Separator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.3</td>
<td>209.51</td>
<td>190%</td>
<td>90%</td>
<td>110.82</td>
<td>WATERFALL</td>
</tr>
<tr>
<td>2</td>
<td>19.8</td>
<td>236.30</td>
<td>60%</td>
<td>90%</td>
<td>113.93</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>16.4</td>
<td>257.79</td>
<td>30%</td>
<td>90%</td>
<td>118.77</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>15.1</td>
<td>257.00</td>
<td>10%</td>
<td>90%</td>
<td>121.02</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>31.1</td>
<td>149.06</td>
<td>90%</td>
<td>10%</td>
<td>110.78</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>31.0</td>
<td>110.96</td>
<td>10%</td>
<td>10%</td>
<td>113.93</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>30.4</td>
<td>234.35</td>
<td>30%</td>
<td>90%</td>
<td>118.77</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>24.6</td>
<td>115.31</td>
<td>90%</td>
<td>10%</td>
<td>110.78</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-15

SEPARATOR TYPE: Patterson 4
OD DIP TUBE= 1”
NUMBER OF SLOTS=8
DIMENSIONS OF THE SLOTS=6” x 3/4”
FLUID ENTERING BELOW THE ANCHOR PORTS

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Flow Meter</th>
<th>Liquid Rate</th>
<th>Gas Rate</th>
<th>Gas Rate Through Separator</th>
<th>Gas Rate Through Separator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.3</td>
<td>209.51</td>
<td>190%</td>
<td>90%</td>
<td>110.82</td>
<td>WATERFALL</td>
</tr>
<tr>
<td>2</td>
<td>19.8</td>
<td>236.30</td>
<td>60%</td>
<td>90%</td>
<td>113.93</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>16.4</td>
<td>257.79</td>
<td>30%</td>
<td>90%</td>
<td>118.77</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>15.1</td>
<td>257.00</td>
<td>10%</td>
<td>90%</td>
<td>121.02</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>31.1</td>
<td>149.06</td>
<td>90%</td>
<td>10%</td>
<td>110.78</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>31.0</td>
<td>110.96</td>
<td>10%</td>
<td>10%</td>
<td>113.93</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>30.4</td>
<td>234.35</td>
<td>30%</td>
<td>90%</td>
<td>118.77</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>24.6</td>
<td>115.31</td>
<td>90%</td>
<td>10%</td>
<td>110.78</td>
<td></td>
</tr>
</tbody>
</table>

146
SEPARATOR TYPE: Patterson 4

OD DIP TUBE = 1"
NUMBER OF ANCHOR PORTS = 8
DIMENSIONS OF THE ANCHOR PORTS = 8" x 3/4"
FLUID ENTERING BELOW THE ANCHOR PORTS
Pc = 10 psi

Figure 5-42
In Figure 5-42, it is noticed that the liquid flow trend curve is almost a horizontal line from 37.14 inches/second to 6.95 inches/second when the liquid velocity is between 9.51 to 12.45 inches/second. These points are shown in the pictures for Test 2, Test 3 and Test 4 in Figure 5-43. The waterfall phenomenon was observed in Tests 1 (Figure 5-43).

In Figure 5-42, it is noticed that when the liquid velocity is between 6.06 and 6.20 inches/second, the gas rate in separator increases from 0.156 MSCFD to 0.461 MSCFD (liquid trend curve). Figure 5-43 (Tests 5, 6, and 7) shows this variation of the gas rate in separator.

Liquid velocity values for design can be obtained from the zero curve. For example, for designing a separator at gas velocity equal to 54.33 inches/second, the liquid velocity must be less than 2.51 inches/second (Figure 5-43, Test 8).

**Figure 5-43: Patterson 4 tests (Fluid entering below the anchor ports at Pc =10 psi)**
C. Anchor Ports Located below the Perforations

This corresponds to the configuration known as “Natural Gas Anchor”. It is observed that there is almost no gas entering the dip tube for this position, this situation was discussed in 5.1 (Position of the Anchor Ports Relative to the Perforations).
5.2.3 Analysis of the Patterson Models with Different Anchor Port Widths

Increasing the width of the anchor port from 1/8 to 3/4 inches, the total cross-sectional area of anchor ports (each separator has eight anchor ports) increases from 8 to 48 square inches.

In Figure 5-44a, the behavior of the Patterson models is shown: Patterson 1 (anchor ports = 8” x 1/8” & dip tube = 1”), Patterson 2 (anchor ports = 8” x 1/4” & dip tube = 1”), Patterson 3 (anchor ports = 8” x 1/2” & dip tube = 1”) and Patterson 4 (anchor ports = 8” x 3/4” & dip tube = 1”). It is noticed that when the fluid is entering in front the anchor ports, increasing the anchor port width reduces the gas rate through the separator.

One of the most important factors that affect the efficiency of downhole gas separators is the superficial liquid velocity (in casing, in separator and in dip tube).

All of the evidence in the present study shows that when the liquid velocity increases, the gas flow through the separator increases. This is because the liquid drags the gas to the dip tube and does not let the gas escape to the annulus. Small liquid velocities help with the separation. It was believed that for liquid velocities in separator less than 6 inches/second, there is good separation, but as this study has demonstrated, the optimum liquid velocity in separator depends also on the factors that have been discussed herein, namely: position of the anchor ports, anchor port width, dip tube diameter and pressure effect.

When the fluid is entering in front the anchor ports, the superficial liquid velocity in casing is equal to the liquid rate entering in the well divided by the total area of the anchor ports (this is because the liquid rate is going directly form the perforations to the anchor ports). By increasing the anchor port width, the area of the anchor ports increases and the liquid velocity in the anchor ports decreases. For example, for a liquid rate Q (BBD), the liquid velocity for Patterson 1 is 0.0281Q inches/second, for Patterson 2 is 0.0140Q inches/second, for Patterson 3 is 0.0070Q inches/second and for Patterson 4 is 0.0047Q inches/second. These velocities are calculated using the area of the bottom
anchor ports, since there is little or no flow through top anchor ports as explained in section 5-4 (Visual Observations).

In Figure 5-45, Table 1 shows the areas for Patterson 1, 2, 3 and 4 for eight anchor ports (top and bottom anchor ports open) and for four anchor ports (bottom anchor ports open). Table 2 shows the velocity ratio $V_1/V_2$ corresponding to the Patterson 1 and 2 separators. Table 3 shows the data for Patterson 1, 2, 3 and 4 when the fluid is entering in front the anchor ports and the $P_c= 10$ psi. Table 4 shows the ratio $Q_1/Q_2$ corresponding to the rates of gas flowing through the separator. Comparing the results between Table 2 and Table 4, it is possible to observe that there is a correlation between the ratios showing that increasing the anchor port width (area) corresponds to a decrease in the gas flowing through the separator when the fluid is entering the casing at the same level as the separator anchor ports.

It is noticed that there is not too much difference in the gas rate in the separator between Patterson 3 and Patterson 4. It is observed that Patterson 3 and Patterson 4 have almost the same behavior; this means that after $\frac{1}{2}$" anchor port width, the behavior is the same—there is no more improvement.

In Figure 5-44b, it is noticed that, when the fluid is entering below the anchor ports, increasing the anchor port width, the gas rate in separator is almost the same for all of the Patterson models. The upwards superficial liquid velocity in the casing is the liquid rate entering in the well divided by the annular area between the casing and the anchor. For example, for a liquid rate $Q$ (BBD) and annular area equal to 5.154 square inches (this is the annular area for all the separators), the superficial liquid velocity in the casing annulus for Patterson 1, Patterson 2, Patterson 3 and Patterson 4 is 0.0279Q inches/second. This is the same order of magnitude of the velocity in the anchor ports for the Patterson 1 separator. Increasing the anchor port area reduces the liquid velocity in the anchor ports below this value but does not affect the gas flow through the separator. This may indicate that in this case the amount of gas flowing into the separator is mostly dependent on the gas present in the annulus and not the area of the anchor ports.
Figure 5-44a

PATTERSONS : FLUID ENTERING IN FRONT THE SLOTS @ 10 psi
Figure 5-44b

PATTERSONS : FLUID ENTERING BELOW THE SLOTS @ 10 psi
Figure 5-45: Analysis of the Patterson models with different anchor port widths

Table 1 Total Slot Area (square inches)

<table>
<thead>
<tr>
<th>NUMBER OF SLOTS</th>
<th>PATTERSON 1</th>
<th>PATTERSON 2</th>
<th>PATTERSON 3</th>
<th>PATTERSON 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eight Slots (TOP+BOTTOM)</td>
<td>8</td>
<td>16</td>
<td>32</td>
<td>48</td>
</tr>
<tr>
<td>Four Slots (BOTTOM)</td>
<td>4</td>
<td>8</td>
<td>16</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 2 Superficial Liquid Velocity Ratios

<table>
<thead>
<tr>
<th>NUMBER OF SLOTS</th>
<th>V1/V2</th>
<th>V1/V3</th>
<th>V1/V4</th>
<th>V2/V3</th>
<th>V2/V4</th>
<th>V3/V4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eight Slots (TOP+BOTTOM)</td>
<td>2.00</td>
<td>4.00</td>
<td>6.00</td>
<td>2.00</td>
<td>3.00</td>
<td>1.50</td>
</tr>
<tr>
<td>Four Slots (BOTTOM)</td>
<td>2.00</td>
<td>4.00</td>
<td>6.00</td>
<td>2.00</td>
<td>3.00</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>SEPARATOR MODEL</th>
<th>Liquid Velocity (inches/second)</th>
<th>Gas Velocity (inches/second)</th>
<th>Gas in Separator (MSCF)</th>
<th>ANNULUS PRESSURE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PATTERSON 1</td>
<td>14.94</td>
<td>54.89</td>
<td>0.239</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>14.94</td>
<td>37.79</td>
<td>0.209</td>
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<tr>
<td></td>
<td>14.94</td>
<td>19.63</td>
<td>0.156</td>
<td>10</td>
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<td>14.94</td>
<td>6.75</td>
<td>0.120</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>11.92</td>
<td>59.42</td>
<td>0.102</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>5.96</td>
<td>60.31</td>
<td>0.000</td>
<td>10</td>
</tr>
<tr>
<td>PATTERSON 2</td>
<td>14.78</td>
<td>55.77</td>
<td>0.132</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>14.58</td>
<td>38.08</td>
<td>0.108</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>14.80</td>
<td>19.78</td>
<td>0.058</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>14.72</td>
<td>6.58</td>
<td>0.041</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>12.51</td>
<td>57.76</td>
<td>0.033</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>5.96</td>
<td>55.64</td>
<td>0.000</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2.19</td>
<td>54.04</td>
<td>0.000</td>
<td>10</td>
</tr>
<tr>
<td>PATTERSON 3</td>
<td>15.09</td>
<td>51.55</td>
<td>0.049</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>14.91</td>
<td>35.02</td>
<td>0.039</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>15.01</td>
<td>18.30</td>
<td>0.034</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>12.38</td>
<td>52.22</td>
<td>0.026</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>12.17</td>
<td>35.35</td>
<td>0.019</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>11.96</td>
<td>18.54</td>
<td>0.017</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>6.12</td>
<td>51.84</td>
<td>0.000</td>
<td>10</td>
</tr>
<tr>
<td>PATTERSON 4</td>
<td>15.06</td>
<td>55.47</td>
<td>0.049</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>15.39</td>
<td>38.53</td>
<td>0.042</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>15.31</td>
<td>19.88</td>
<td>0.032</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>12.39</td>
<td>55.67</td>
<td>0.000</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>6.04</td>
<td>55.09</td>
<td>0.000</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 4 Ratios of Gas through Separators

<table>
<thead>
<tr>
<th>Q1/Q2</th>
<th>Q1/Q3</th>
<th>Q1/Q4</th>
<th>Q2/Q3</th>
<th>Q2/Q4</th>
<th>Q3/Q4</th>
<th>AVERAGE</th>
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</thead>
<tbody>
<tr>
<td>1.8</td>
<td>4.9</td>
<td>5.3</td>
<td>2.7</td>
<td>2.9</td>
<td>1.1</td>
<td>3.1</td>
</tr>
<tr>
<td>1.9</td>
<td>5.4</td>
<td>5.0</td>
<td>2.8</td>
<td>2.6</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>2.7</td>
<td>4.9</td>
<td>1.7</td>
<td>1.8</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.9</td>
<td>6.0</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

V1: Superficial Liquid Velocity in Patterson 1
V2: Superficial Liquid Velocity in Patterson 2
V3: Superficial Liquid Velocity in Patterson 3
V4: Superficial Liquid Velocity in Patterson 4
Q1: Gas Rate in Separator at Standard Conditions for Patterson 1
Q2: Gas Rate in Separator at Standard Conditions for Patterson 2
Q3: Gas Rate in Separator at Standard Conditions for Patterson 3
Q4: Gas Rate in Separator at Standard Conditions for Patterson 4
5.3 Effect of Dip Tube Diameter on Separator Efficiency

Dip tube diameter is another parameter that is studied in this project. The most important parameter is the effect on the liquid superficial velocity in the separator VL which can vary by changing the dip tube area A (VL=Q/A).

VL= Liquid Superficial Velocity in the Separator
Q= Liquid Rate
A= Inside Dip Tube Area.

A dip tube outside diameter of 1” (ID = 0.75” and ID AREA = 0.442 sq. inches) and 1.5” (ID = 1.28” and ID AREA = 1.287 sq. inches) was used.

5.3.1 Patterson Models

Patterson 5 and Patterson 6 were constructed by changing the dip tube diameter from 1” OD to 1.5” OD using the Patterson 3 and Patterson 4 models, respectively.

Patterson 5 and Patterson 3 are used in the discussion of the effect of the dip tube because they have a behavior similar to that of Patterson 4 and Patterson 6.

Figure 5-46 (5-45a and 5-46b) shows the Patterson 5 and the Patterson 3 models. It is observed in the pictures that Patterson 5 and Patterson 3 have eight anchor ports. Each anchor port is 8 inches long and a 1/2 inch wide. The dip tube for Patterson 3 is 1 inch OD and 3/4 inch ID and for Patterson 5, it is 1.5 inches OD and 1.28 inches ID.
Tables 5-16 and 5-12 show the data obtained from the test and the data calculated for Patterson 5 and Patterson 3, respectively, when the fluid is entering in front the anchor ports and the casing pressure is 10 psi.

**Fluid Entering in Front the Anchor Ports**

Tables 5-16 and 5-12 show the data obtained from the test and the data calculated for Patterson 5 and Patterson 3, respectively, when the fluid is entering in front the anchor ports and the casing pressure is 10 psi.
Table 5-16

SEPARATOR TYPE: Patterson 5
OD DIP TUBE: 1.5"
NUMBER OF SLOTS: 8
DIMENSIONS OF THE SLOTS: 8" x 1/2"
POSITION OF THE SEPARATOR: IN FRONT THE PERFORATIONS

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Floco Meter</th>
<th>Liquid Rate</th>
<th>Gas Rate BBD</th>
<th>Gas Rate</th>
<th>Gas Rate</th>
<th>Gas Rate</th>
<th>Gas Rate</th>
<th>Gas Rate</th>
<th>Gas Rate</th>
<th>Gas Rate</th>
<th>Gas Rate</th>
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<th>Gas Rate</th>
<th>Gas Rate</th>
<th>Gas Rate</th>
<th>Gas Rate</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Meter</td>
<td>Rate</td>
<td>BSCF</td>
<td>Pressure</td>
<td>Minimum</td>
<td>Maximum</td>
<td>Minimum</td>
<td>Maximum</td>
<td>Minimum</td>
<td>Maximum</td>
<td>Minimum</td>
<td>Maximum</td>
<td>Minimum</td>
<td>Maximum</td>
</tr>
<tr>
<td>1</td>
<td>FL-3820C</td>
<td>90%</td>
<td>12.8</td>
<td>675.00</td>
<td>90%</td>
<td>14.78</td>
<td>108.05</td>
<td>108.66</td>
<td>10.5</td>
<td>9.5</td>
<td>7.8</td>
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<td>6.0</td>
<td>5.4</td>
<td>5.4</td>
<td>14.72</td>
<td>3.56</td>
</tr>
<tr>
<td>2</td>
<td>FL-3839ST</td>
<td>60%</td>
<td>12.7</td>
<td>680.31</td>
<td>60%</td>
<td>9.86</td>
<td>112.99</td>
<td>75.74</td>
<td>10.6</td>
<td>9.5</td>
<td>8.0</td>
<td>7.0</td>
<td>6.1</td>
<td>5.4</td>
<td>14.83</td>
<td>3.61</td>
<td>38.84</td>
</tr>
<tr>
<td>3</td>
<td>FL-50000</td>
<td>30%</td>
<td>12.6</td>
<td>685.71</td>
<td>30%</td>
<td>4.93</td>
<td>118.08</td>
<td>39.53</td>
<td>10.4</td>
<td>9.5</td>
<td>7.8</td>
<td>7.0</td>
<td>6.0</td>
<td>5.6</td>
<td>14.95</td>
<td>3.63</td>
<td>20.38</td>
</tr>
<tr>
<td>4</td>
<td>FL-48920</td>
<td>10%</td>
<td>12.5</td>
<td>691.20</td>
<td>10%</td>
<td>1.64</td>
<td>120.42</td>
<td>13.45</td>
<td>9.8</td>
<td>10.0</td>
<td>7.5</td>
<td>7.0</td>
<td>5.6</td>
<td>5.4</td>
<td>15.07</td>
<td>3.58</td>
<td>6.94</td>
</tr>
<tr>
<td>5</td>
<td>FL-48900</td>
<td>60%</td>
<td>19.2</td>
<td>450.00</td>
<td>60%</td>
<td>14.78</td>
<td>122.97</td>
<td>109.58</td>
<td>10.5</td>
<td>10.0</td>
<td>8.2</td>
<td>7.5</td>
<td>6.4</td>
<td>6.0</td>
<td>9.81</td>
<td>2.36</td>
<td>55.66</td>
</tr>
<tr>
<td>6</td>
<td>FL-48900</td>
<td>30%</td>
<td>19.4</td>
<td>445.30</td>
<td>30%</td>
<td>9.68</td>
<td>113.10</td>
<td>75.86</td>
<td>10.5</td>
<td>10.0</td>
<td>8.1</td>
<td>7.5</td>
<td>6.4</td>
<td>6.1</td>
<td>9.71</td>
<td>2.36</td>
<td>38.92</td>
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<tr>
<td>7</td>
<td>FL-48900</td>
<td>10%</td>
<td>19.6</td>
<td>440.82</td>
<td>10%</td>
<td>4.92</td>
<td>117.65</td>
<td>39.61</td>
<td>10.5</td>
<td>10.0</td>
<td>8.2</td>
<td>7.5</td>
<td>6.4</td>
<td>6.0</td>
<td>9.63</td>
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<td>20.06</td>
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<td>FL-48900</td>
<td>60%</td>
<td>19.8</td>
<td>443.08</td>
<td>60%</td>
<td>16.64</td>
<td>120.42</td>
<td>13.45</td>
<td>10.0</td>
<td>10.0</td>
<td>8.2</td>
<td>7.5</td>
<td>6.3</td>
<td>6.2</td>
<td>9.81</td>
<td>2.33</td>
<td>6.82</td>
</tr>
<tr>
<td>9</td>
<td>FL-48900</td>
<td>30%</td>
<td>20.1</td>
<td>446.15</td>
<td>30%</td>
<td>16.74</td>
<td>108.79</td>
<td>103.72</td>
<td>11.5</td>
<td>10.0</td>
<td>8.2</td>
<td>7.5</td>
<td>6.4</td>
<td>6.2</td>
<td>9.77</td>
<td>1.30</td>
<td>55.56</td>
</tr>
</tbody>
</table>

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SEPARATOR TYPE: Patterson 5

OD DIP TUBE = 1.5"
NUMBER OF ANCHOR PORTS = 8
DIMENSIONS OF THE ANCHOR PORTS = 8" x 1/2"
FLUID ENTERING IN FRONT THE ANCHOR PORTS
Pc = 10 psi

**Figure 5-47**

![Graph](image-url)

- **Superficial Liquid Velocity** inside Separator (in/sec)
- **Superficial Gas Velocity** in casing annulus (in/sec)
- **Gas Rate through Separator (MSCF/day)**
Increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate flowing through the separator.

In Figure 5-47, it is noticed that when the liquid velocity is between 18.31 and 18.53 inches/second, the gas rate in separator increases from 0.052 MSCFD to 0.138 MSCFD (Figure 5-48, Tests 1, 2 and 3).

The flow pattern in the pictures is shown to be a bubble flow, but these bubbles are very small (in Table 5-16, they are described as microscopic bubbles).

When the liquid velocity is between 11.83 to 12.12 inches/second, the gas rate in separator increases from 0.022 MSCFD to 0.039 MSCFD (Figure 5-48, Tests 4, 5, 6 and 7).

When the liquid velocity is 6.62 inches/second and the gas velocity is 55.58 inches/second, the gas rate in separator is 0.006 (Figure 5-48, Test 9).

**Figure 5-48: Patterson 5 tests (Fluid entering in front the anchor ports at Pc =10 psi)**

![Test 1](image1.png) ![Test 2](image2.png)
Figure 5-48 – continued
In Figure 5-49, the pictures are shown side by side to compare the tests under the same conditions for Patterson 3 and Patterson 5.

**Figure 5-49: Patterson 3 vs Patterson 5 (Fluid entering in front the anchor ports at $P_c = 10$ psi)**

- **Test 4 Patterson 3**
  (VL= 12.38 inch/se, VG= 52.22 inch/sec)

- **Test 5 Patterson 5**
  (VL= 12.12 inch/se, VG= 55.43 inch/sec)
**Fluid Entering Below the Anchor Ports**

Tables 5-17 and 5-13 show the data obtained from the tests and the data calculated for Patterson 5 and Patterson 3, respectively, when the fluid is entering below the anchor ports and the casing pressure is 10 psi.
Table 5-17

Date 7/21/2004

SEPARATOR TYPE: Patterson 5
OD DIP TUBE= 1.5"
NUMBER OF SLOTS=8
DIMENSIONS OF THE SLOTS=8" x 1/2"
FLUID ENTERING BELOW THE ANCHOR PORTS

| Test N° | Floco Meter | Liquid Rate | Gas Rate MCF | Gas Rate SCFM | Annulus Pressure Maximum | Annulus Pressure Minimum | Ports Pressure Minimum | Ports Pressure Maximum | Tubing Pressure Minimum | Tubing Pressure Maximum | Superficial Liquid Velocity in Separator | Superficial Liquid Velocity in Casing | Superficial Gas Velocity in Casing | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator |
|---------|-------------|-------------|--------------|---------------|--------------------------|------------------------|----------------------|----------------------|------------------------|------------------------|----------------------------------------|-------------------------------|-----------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| 1       | 15.6        | 553.14      | 14.78        | 108.88        | 108.99                  | 12.5                   | 11.5                 | 10.5                 | 9.5                    | 8.8                    | 8.8                       | 14.88                          | 2.93                         | 51.47                        | 1.28                      | 1.843                     | WATERFALL                 | WATERFALL                 | WATERFALL                 | WATERFALL                 |
| 2       | 15.9        | 543.05      | 9.86         | 113.15        | 75.86                   | 12.5                   | 11.5                 | 10.5                 | 10.0                   | 8.2                    | 8.2                       | 14.61                          | 2.88                         | 35.82                        | 1.80                      | 1.728                     | WATERFALL                 | WATERFALL                 | WATERFALL                 | WATERFALL                 |
| 3       | 15.8        | 547.18      | 30%          | 118.77        | 39.81                   | 12.0                   | 11.0                 | 9.5                  | 9.0                    | 7.2                    | 7.2                       | 14.72                          | 2.99                         | 19.19                        | 1.05                      | 1.512                     | WATERFALL                 | WATERFALL                 | WATERFALL                 | WATERFALL                 |
| 4       | 15.7        | 540.27      | 10%          | 121.28        | 13.03                   | 10.5                   | 9.5                  | 8.0                  | 7.0                    | 6.3                    | 6.3                       | 14.78                          | 2.91                         | 6.95                         | 0.73                      | 1.044                     | WATERFALL                 | WATERFALL                 | WATERFALL                 | WATERFALL                 |
| 5       | 35.0        | 246.65      | 90%          | 14.78        | 115.30                  | 10.0                   | 9.5                  | 8.5                  | 8.0                    | 6.0                    | 6.0                       | 8.03                           | 1.31                         | 58.25                        | 110                      | 0.859                     | WATERFALL                 | WATERFALL                 | WATERFALL                 | WATERFALL                 |
| 6       | 34.9        | 247.78      | 60%          | 114.25        | 76.62                   | 10.5                   | 9.5                  | 7.0                  | 6.5                    | 6.4                    | 6.4                       | 13.71                          | 0.79                         | 44.14                        | 0.363                     | 0.031                     | WATERFALL                 | WATERFALL                 | WATERFALL                 | WATERFALL                 |
| 7       | 35.0        | 246.88      | 30%          | 114.68        | 39.79                   | 10.5                   | 10.0                 | 8.1                  | 7.0                    | 6.3                    | 6.3                       | 6.64                           | 1.31                         | 20.62                        | 22                       | 0.122                     | WATERFALL                 | WATERFALL                 | WATERFALL                 | WATERFALL                 |
| 8       | 35.1        | 246.36      | 10%          | 120.15        | 13.43                   | 11.0                   | 10.5                 | 8.5                  | 8.1                    | 7.0                    | 7.0                       | 6.63                           | 1.31                         | 6.75                         | 5                        | 0                        | 0                          | 0.000                     |

DIMENSIONS OF THE SLOTS=8” x 1/2”
FLUID ENTERING BELOW THE ANCHOR PORTS
SEPARATOR TYPE: Patterson 5

OD DIP TUBE = 1.5"
NUMBER OF ANCHOR PORTS = 8
DIMENSIONS OF THE ANCHOR PORTS = 8" x 1/2"
FLUID ENTERING BELOW THE ANCHOR PORTS
Pc = 10 psi

Figure 5-50

Superficial Gas Velocity in casing annulus (in/sec) vs. Superficial Liquid Velocity inside Separator (in/sec)

Gas Rate through Separator (MSCF/day)
Increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate flowing through the separator.

In Figure 5-50, it is noticed that when the liquid velocity is between 14.61 and 14.88 inches/second, the gas rate in separator increases from 1.044 MSCFD to 1.843 MSCFD (liquid trend curve). Figure 5-51 (Tests 1, 2, 3 and 4) shows this variation of the gas rate in separator. The waterfall phenomenon was observed in Tests 1, 2 and 3 (Figure 5-51).

It is observed in Figure 5-50 that, when the liquid velocity is between 6.63 and 6.67 inches/second, the gas rate in separator increases from almost 0 MSCFD to 0.658 MSCFD (liquid trend curve). Figure 5-51 (Tests 5, 6 and 7) shows these differences very clearly.

**Figure 5-51: Patterson 5 tests (Fluid entering below the anchor ports at Pc =10 psi)**
In Figure 5-49, the pictures are shown side by side to compare the tests under the same conditions for Patterson 3 and Patterson 5.
Figure 5-52: Patterson 3 vs Patterson 5 (Fluid entering below the anchor ports at Pc =10 psi)

Test 5 Patterson 3
(VL= 5.99 inch/sec, VG= 56.71 inch/sec)

Test 5 Patterson 5
(VL= 6.63 inch/sec, VG= 56.25 inch/sec)

Test 6 Patterson 3
(VL= 6.03 inch/sec, VG= 39.19 inch/sec)

Test 6 Patterson 5
(VL= 6.67 inch/sec, VG= 39.11 inch/sec)

Test 7 Patterson 3
(VL= 6.06 inch/sec, VG= 20.03 inch/sec)

Test 7 Patterson 5
(VL= 6.64 inch/sec, VG= 20.00 inch/sec)
5.3.2 Analysis of the effect of Dip Tube Diameter on the performance of the Patterson Models

Increasing the dip tube diameter increases the gas rate in separator. Due to the dip tube diameter being greater, at the same liquid rate, the superficial velocities of the gas and liquid inside separator are greater \( V = \frac{Q}{A} \).

- \( VL = \) Liquid Superficial Velocity in the Separator
- \( Q = \) Liquid Rate
- \( A = \) Inside Dip Tube Area.

To better compare the behavior of Patterson 3 and Patterson 5, the superficial velocities are used.

Independently of the position (fluid is entering in front or below the anchor ports), it shows the same behavior; the volume of gas is increased by almost 33% for the same liquid and gas velocities (Figures 5-53 and 5-54).

Increasing the dip tube diameter decreases the pressure drop in the system. Pressure drop in the system is the difference between the pressure in the tubing (P2) and the pressure in the anchor ports (P1). Figure 5-55 shows P1 and P2.

For field application, P2 will be considered to be also equal to the pressure in the pump, assuming there are no additional pressure losses through the intake valve.

Pressure drop in the system (P2-P1) depends on different variables such as dip tube length and diameter and any area restriction that generates a pressure loss.
Figure 5-53
PATTERSON 3 VS PATTERSON 5
FLUID ENTERING IN FRONT THE SLOTS @ 10 psi

Gas Rate through Separator (MSCF)

Superficial Gas Velocity in casing annulus (in/sec)
Superficial Liquid Velocity inside Separator (in/sec)

Patterson 3
Patterson 5
Figure 5-54

PATTERSON 3 VS PATTERSON 5
FLUID ENTERING BELOW THE SLOTS @ 10 psi
In the oil industry, a long downhole gas separator is usually used to get a good separation. In this project, it is shown that it is not necessary to use a long downhole gas separator to get an excellent gas separation. A downhole gas separator 6 feet long (5.5-foot dip tube) is enough to achieve efficient gas separation and with this geometry the pressure loss in the system due to the longitude of the diptube is reduced.

In the tests, there were pressure drops of 5 psi occurring with only a 5.5 ft dip tube length. Using 20 or 40 ft, the pressure drop due to the length of the diptube would be much greater. Figure 5-55 shows the location of Pc, P1, P2, P3 and P4. Figures 5-56 and 5-57 show different liquid rates and pressure values measured and calculated for Patterson 5 and 3, respectively. These tests were made using 100% water to obtain stable conditions and when the fluid is entering in front the anchor ports.

When the fluid is entering in front the anchor ports, as in the case of Patterson 5 (anchor ports=8” x 1/2” & dip tube = 1.5”), the pressure drop in the system is almost constant (straight line), with a maximum value of 1.6 psi and a minimum value of 1.2 psi. In the case of Patterson 3 (anchor ports=8” x 1/2” & dip tube = 1”), the pressure drop increases considerably with the liquid rate, the maximum value is 4.5 psi and the minimum value is 0.8 psi.
Figure 5-55: Location of the manometers to measure Pc, P1, P2, P3 and P4
Figure 5-56

SEPARATOR TYPE: Patterson 5
Fluid entering in front the anchor ports
100 % WATER

<table>
<thead>
<tr>
<th>Floco Meter (sec/0.1BBD)</th>
<th>Q (bbd)</th>
<th>Pc (psi)</th>
<th>P1 (psi)</th>
<th>P2 (Hg)</th>
<th>Delta P (P1-P2) (psi)</th>
<th>P2 (calculated) (psi)</th>
<th>Delta P (P1-P2) (psi)</th>
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<td>6.0</td>
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<td>1.7</td>
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<td>14.76</td>
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<td>10.3</td>
<td>7.5</td>
<td>6.0</td>
<td>1.5</td>
<td>6.31</td>
<td>1.2</td>
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<td>7.3</td>
<td>5.8</td>
<td>1.5</td>
<td>6.33</td>
<td>1.0</td>
</tr>
<tr>
<td>35.20</td>
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<td>10.4</td>
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<td>6.0</td>
<td>1.4</td>
<td>6.47</td>
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<td>6.12</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Delta P vs Rate

- Measured
- Calculated
- Linear (Measured)
- Exponential (Calculated)

y = 0.0006x + 1.2201
R² = 0.7622

y = 0.8096e^0.0007x
R² = 0.9901
Figure 5-57

SEPARATOR TYPE: Patterson 3
Fluid entering in front the anchor ports
100 % WATER

<table>
<thead>
<tr>
<th>Floco Meter (sec/0.1BBi)</th>
<th>Q (bbd)</th>
<th>Pc (psi)</th>
<th>P1 (psi)</th>
<th>P2 (psi)</th>
<th>deltaP (P1-P2)</th>
<th>P2 (calculated)</th>
<th>deltaP (P1-P2)</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
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<td>4.54</td>
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<td>1.9</td>
<td>5.38</td>
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<td>0.8</td>
<td>6.34</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Delta P vs Rate

\[
y = 0.7889e^{0.003x}
\]

\[
R^2 = 0.9966
\]

\[
y = 0.0065x - 0.0244
\]

\[
R^2 = 0.9847
\]
Figures 5-58 and 5-59 show different liquid rates and pressure values measured and calculated for Patterson 5 and 3, respectively. These tests were made using 100% water to get stable conditions and when the fluid is entering below the anchor ports.

The same behavior is shown when the fluid is entering below the anchor ports, as in the case of Patterson 5 (anchor ports = 8” x 1/2” & dip tube = 1.5”), the maximum value is 1.9 psi and a minimum value of 1 psi. In the case of Patterson 3 (anchor ports = 8” x 1/2” & dip tube = 1”), the pressure drop increases with the liquid rate, the maximum value is 4.5 psi and the minimum value is 0.8 psi.

Tables 5-18 and 5-19 show the calculation of P2 for Patterson 3 and Patterson 5, respectively (the description of this table is in Appendix E). Figures 5-60 and 5-61 show P2 calculated vs. P2 measured for Patterson 5 and Patterson 3, respectively. On these graphs, a 45° line was plotted to see the difference between the calculated and measured values. It is observed that the calculated and measured values are very similar; therefore, in the field we can calculate the P2.
Figure 5-58

SEPARATOR TYPE: Patterson 5
Fluid entering below the anchor ports
100 % WATER

<table>
<thead>
<tr>
<th>Floco Meter (sec/ 0.1BBI)</th>
<th>Q (bbd)</th>
<th>Pc (psi)</th>
<th>P1 (psi)</th>
<th>P2 (psi)</th>
<th>P2 (calculated)</th>
<th>Delta P (P1-P2) (psi)</th>
<th>Delta P (P1-P2) (calculated)</th>
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<tbody>
<tr>
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</table>

Delta P vs Rate

- Measured
- Calculated
- Linear (Measured)
- Exponential (Calculated)

\[ y = 0.001x + 0.932 \]
\[ R^2 = 0.9178 \]

\[ y = 0.7907e^{0.0007x} \]
\[ R^2 = 0.9904 \]
# Figure 5-59

**SEPARATOR TYPE:** Patterson 3

**Fluid entering below the anchor ports**

**100 % WATER**

<table>
<thead>
<tr>
<th>Floco Meter (sec/ 0.1BBl)</th>
<th>Q (bbd)</th>
<th>Pc (psi)</th>
<th>P1 (psi)</th>
<th>P2 (psi)</th>
<th>Hg</th>
<th>Delta P (P1-P2) (psi)</th>
<th>P2 (calculated)</th>
<th>Delta P (P1-P2) (psi)</th>
</tr>
</thead>
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<td>648.74</td>
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<tr>
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<td>0.8</td>
<td>6.33</td>
<td>1.1</td>
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</table>

**Delta P vs Rate**

- **Measured**
- **Calculated**
- **Linear (Measured)**
- **Exponential (Calculated)**

**Equations:**

1. \( y = 0.7886e^{0.003x} \)
   \( R^2 = 0.9962 \)

2. \( y = 0.0067x - 0.0436 \)
   \( R^2 = 0.9913 \)
### Table 5-18: Calculation of P2 for Patterson 3

<table>
<thead>
<tr>
<th>Qlestrate (bbd)</th>
<th>Vdiptube anchor (m/s)</th>
<th>Rediptube/a</th>
<th>Vdiptube</th>
<th>Rediptube</th>
<th>factorHope of anchor</th>
<th>P4 (psi)</th>
<th>P1 (psi)</th>
<th>P2 (psi)</th>
<th>Vtubing</th>
<th>Retubing</th>
<th>factorTubing</th>
<th>1/2 ρ<em>AV</em>2</th>
<th>P3 (psi)</th>
<th>P2 (calculated)</th>
<th>P2 (measured)</th>
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#### BELOW THE PERFORATIONS

### Table 5-19: Calculation of P2 for Patterson 5

<table>
<thead>
<tr>
<th>Qlestrate (bbd)</th>
<th>Vdiptube anchor (m/s)</th>
<th>Rediptube/a</th>
<th>Vdiptube</th>
<th>Rediptube</th>
<th>factorHope of anchor</th>
<th>P4 (psi)</th>
<th>P1 (psi)</th>
<th>P2 (psi)</th>
<th>Vtubing</th>
<th>Retubing</th>
<th>factorTubing</th>
<th>1/2 ρ<em>AV</em>2</th>
<th>P3 (psi)</th>
<th>P2 (calculated)</th>
<th>P2 (measured)</th>
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<tbody>
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<td>6945</td>
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<td>0.15790</td>
<td>1680</td>
<td>0.01268</td>
<td>-0.5256</td>
<td>5.2222</td>
<td>4.57186</td>
<td>4.5000</td>
</tr>
<tr>
<td>303</td>
<td>0.1688</td>
<td>7.4</td>
<td>2969</td>
<td>0.0109</td>
<td>9.3505</td>
<td>1.9694</td>
<td>5070</td>
<td>0.0932</td>
<td>0.11527</td>
<td>1227</td>
<td>0.01440</td>
<td>-0.2802</td>
<td>6.06812</td>
<td>5.41795</td>
<td>5.5000</td>
</tr>
<tr>
<td>195</td>
<td>0.1088</td>
<td>7.4</td>
<td>1914</td>
<td>0.0124</td>
<td>9.3500</td>
<td>1.2977</td>
<td>3269</td>
<td>0.0105</td>
<td>0.07432</td>
<td>791</td>
<td>0.01675</td>
<td>-0.1165</td>
<td>6.67251</td>
<td>6.02250</td>
<td>6.2000</td>
</tr>
<tr>
<td>116</td>
<td>0.0645</td>
<td>7.4</td>
<td>1134</td>
<td>0.0148</td>
<td>9.3497</td>
<td>0.7520</td>
<td>1936</td>
<td>0.0124</td>
<td>0.04402</td>
<td>468</td>
<td>0.02028</td>
<td>-0.0408</td>
<td>6.97965</td>
<td>6.33004</td>
<td>6.6000</td>
</tr>
</tbody>
</table>

#### IN FRONT THE PERFORATIONS

#### BELOW THE PERFORATIONS
Figure 5-60

**P2 calculated vs P2 Measured**

SEPARATOR TYPE: Patterson 5
(100 % WATER)

Pc=5 & 10 psi

- 5 psi (in front ports)
- 10 psi (in front ports)
- 45° line
- 5 psi (below ports)
- 10 psi (below ports)
Figure 5-61

P2 calculated vs P2 Measured
SEPARATOR TYPE: Patterson 3
(100 % WATER)
Pc=5 & 10 psi

P2 Calculated (psi)
P2 Measured (psi)

-4.0 -2.0 0.0 2.0 4.0 6.0 8.0 10.0

5 psi (in front ports)
10 psi (in front ports)
45° line
5 psi (below ports)
10 psi (below ports)
5.3.3 Echometer Models

Echometer 1 and Echometer 2 are used to discuss the effect of the dip tube. Figure 5-62 (5-62 and 5-62b) shows the Echometer 1 and the Echometer 2 models. It is observed in the pictures that Echometer 1 and Echometer 2 have four anchor ports. Each anchor port is 4 inches long and 2 inches wide. The dip tube for Echometer 1 is 1 inch OD and 3/4 inch ID and for Echometer 2, it is 1.5 inches OD and 1.28 inches ID.

Figure 5-62: Echometer 1 and Echometer 2

Figure 5-62a: Echometer 1

Figure 5-62b: Echometer 2

Fluid Entering in Front the Anchor Ports

Tables 5-4 and 5-20 show the data obtained from the test and the data calculated for Echometer 1 and Echometer 2, respectively, when the fluid is entering in front the anchor ports and the casing pressure is 10 psi.
Table 5-20

**SEPARATOR TYPE:** Echometer 2  
**OD DIP TUBE:** 1.5"  
**NUMBER OF SLOTS:** 4  
**DIMENSIONS OF THE SLOTS:** 2" x 4"  
**FLUID ENTERING IN FRONT THE ANCHOR PORTS**

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Floco N°</th>
<th>Liquid Rate (sec/0.1Bbl)</th>
<th>BBD</th>
<th>%</th>
<th>D</th>
<th>psi</th>
<th>D</th>
<th>psi</th>
<th>(Hg)</th>
<th>(Hg)</th>
<th>(psi)</th>
<th>(psi)</th>
<th>(psi)</th>
<th>(psi)</th>
<th>(Hg)</th>
<th>(Hg)</th>
<th>Inches/sec</th>
<th>Inches/sec</th>
<th>FL-3839ST</th>
<th>FL-3839ST</th>
<th>MSCF</th>
<th>MSCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.1</td>
<td>409.48</td>
<td>90%</td>
<td>14.78</td>
<td>109.35</td>
<td>11.0</td>
<td>10.0</td>
<td>8.5</td>
<td>7.5</td>
<td>5.4</td>
<td>5.0</td>
<td>11.0</td>
<td>2.17</td>
<td>55.29</td>
<td>0.73</td>
<td>1.05</td>
<td>WATERFALL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>21.2</td>
<td>406.78</td>
<td>60%</td>
<td>9.66</td>
<td>114.28</td>
<td>10.5</td>
<td>9.9</td>
<td>7.4</td>
<td>6.8</td>
<td>5.2</td>
<td>5.0</td>
<td>10.9</td>
<td>2.16</td>
<td>39.03</td>
<td>0.67</td>
<td>0.95</td>
<td>PARTIAL WATERFALL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>21.6</td>
<td>399.81</td>
<td>30%</td>
<td>4.63</td>
<td>116.79</td>
<td>10.7</td>
<td>10.0</td>
<td>7.5</td>
<td>7.0</td>
<td>4.0</td>
<td>6.0</td>
<td>10.9</td>
<td>10.9</td>
<td>10.9</td>
<td>10.9</td>
<td>10.9</td>
<td>10.9</td>
<td>39.0</td>
<td>39.0</td>
<td>0.71</td>
<td>0.71</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>21.1</td>
<td>397.61</td>
<td>10%</td>
<td>1.64</td>
<td>119.98</td>
<td>10.5</td>
<td>10.0</td>
<td>7.5</td>
<td>7.0</td>
<td>5.9</td>
<td>5.9</td>
<td>10.7</td>
<td>2.11</td>
<td>6.81</td>
<td>0.70</td>
<td>0.41</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>36.5</td>
<td>239.20</td>
<td>60%</td>
<td>14.78</td>
<td>108.33</td>
<td>10.9</td>
<td>10.0</td>
<td>7.5</td>
<td>7.0</td>
<td>4.0</td>
<td>6.0</td>
<td>6.3</td>
<td>1.27</td>
<td>95.00</td>
<td>0.48</td>
<td>0.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>21.5</td>
<td>235.29</td>
<td>30%</td>
<td>4.63</td>
<td>114.19</td>
<td>11.0</td>
<td>10.2</td>
<td>7.8</td>
<td>7.2</td>
<td>6.0</td>
<td>5.8</td>
<td>6.3</td>
<td>1.25</td>
<td>35.33</td>
<td>0.34</td>
<td>0.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>36.9</td>
<td>240.87</td>
<td>30%</td>
<td>4.63</td>
<td>117.56</td>
<td>11.0</td>
<td>10.5</td>
<td>8.5</td>
<td>7.5</td>
<td>6.0</td>
<td>6.0</td>
<td>6.4</td>
<td>1.28</td>
<td>19.60</td>
<td>0.26</td>
<td>0.12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>36.3</td>
<td>238.11</td>
<td>10%</td>
<td>1.64</td>
<td>114.32</td>
<td>12.71</td>
<td>10.5</td>
<td>10.0</td>
<td>7.4</td>
<td>6.9</td>
<td>6.0</td>
<td>6.0</td>
<td>6.4</td>
<td>1.27</td>
<td>6.49</td>
<td>0.17</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>36.2</td>
<td>230.31</td>
<td>60%</td>
<td>14.78</td>
<td>110.52</td>
<td>11.0</td>
<td>10.5</td>
<td>8.5</td>
<td>7.5</td>
<td>6.4</td>
<td>6.2</td>
<td>3.25</td>
<td>0.64</td>
<td>96.49</td>
<td>0</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SEPARATOR TYPE: Echometer 2

OD DIP TUBE = 1.5"
NUMBER OF ANCHOR PORTS = 4
DIMENSIONS OF THE ANCHOR PORTS = 2" x 4"
FLUID ENTERING IN FRONT THE ANCHOR PORTS
 Pc = 10 psi

Figure 5-63
Increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate flowing through the separator.

In Figure 5-63, it is noticed that when the liquid velocity is between 10.70 and 11.01 inches/second, the gas rate in separator increases from 0.419 MSCFD to 1.051 MSCFD (liquid trend curve). Figure 5-64 (Test 1, Test 2, Test 3 and Test 4 for Echometer 2) shows these differences. The waterfall phenomenon was observed in Tests 1 and 2 for Echometer 2 and Test 1 for Echometer 1 (Figure 5-64).

When the liquid velocity is between 6.33 to 6.48 inches/second, the gas rate in separator increases from 0.102 MSCFD to 0.275 MSCFD (Figure 5-64, Tests 5, 6, 7 and 8 for Echometer 2).

When the liquid velocity is 3.26 inches/second and the gas velocity is 56.49 inches/second, the gas rate in separator is 0 (Figure 5-64, Test 9 Echometer 2).

In Figure 5-64, the pictures are shown side by side to compare the tests under the same conditions for Echometer 1 and Echometer 2.

**Figure 5-64: Echometer 1 vs Echometer 2 (Fluid entering in front the anchor ports at Pc =10 psi)**

<table>
<thead>
<tr>
<th>Test 1 Echometer 1</th>
<th>Test 1 Echometer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(VL= 10.77 inch/se, VG= 57.17 inch/sec)</td>
<td>(VL= 11.01 inch/se, VG= 55.29 inch/sec)</td>
</tr>
</tbody>
</table>
Figure 5-64 – continued

Test 2 Echometer 1
(VL= 10.76 inch/se, VG= 38.46 inch/sec)

Test 2 Echometer 2
(VL= 10.94 inch/se, VG= 39.03 inch/sec)

Test 3 Echometer 1
(VL= 10.93 inch/se, VG= 19.69 inch/sec)

Test 3 Echometer 2
(VL= 10.76 inch/se, VG= 19.81 inch/sec)

Test 4 Echometer 1
(VL= 11.04 inch/se, VG= 7.02 inch/sec)

Test 4 Echometer 2
(VL= 10.70 inch/se, VG= 6.81 inch/sec)
Figure 5-64 – continued

Test 5 Echometer 1
(VL= 6.25 inch/sec, VG= 54.82 inch/sec)

Test 5 Echometer 2
(VL= 6.43 inch/sec, VG= 55.00 inch/sec)

Test 6 Echometer 1
(VL= 6.31 inch/sec, VG= 38.59 inch/sec)

Test 6 Echometer 2
(VL= 6.33 inch/sec, VG= 38.33 inch/sec)

Test 7 Echometer 1
(VL= 6.28 inch/sec, VG= 20.13 inch/sec)

Test 7 Echometer 2
(VL= 6.48 inch/sec, VG= 19.60 inch/sec)
Figure 5-64 – continued

Test 8 Echometer 1
(VL= 2.33 inch/se, VG= 58.19 inch/sec)

Test 9 Echometer 2
(VL= 3.28 inch/se, VG= 56.49 inch/sec)

Fluid Entering Below the Anchor Ports

Tables 5-21 and 5-5 show the data obtained from the tests and the data calculated for Echometer 1 and Echometer 2, respectively, when the fluid is entering below the anchor ports and the casing pressure is 10 psi.
Table 5-21

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Flow Meter</th>
<th>Liquid Rate</th>
<th>Gas Rate</th>
<th>Gas Rate Meter Pressure</th>
<th>Gas Rate MCF</th>
<th>Anulus Pressure Minimum</th>
<th>Anulus Pressure Maximum</th>
<th>Ports Pressure Minimum</th>
<th>Ports Pressure Maximum</th>
<th>Tubing Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Tubing Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Superficial Liquid Velocity in Separator</th>
<th>Superficial Liquid Velocity in Casing</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.8</td>
<td>482.14</td>
<td>90%</td>
<td>6.75</td>
<td>109.97</td>
<td>12.0</td>
<td>11.5</td>
<td>11.0</td>
<td>10.4</td>
<td>8.0</td>
<td>8.0</td>
<td>12.97</td>
<td>12.97</td>
<td>2.95</td>
<td>91.93</td>
<td>1.19</td>
<td>1.71</td>
<td>WATERFALL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>17.7</td>
<td>487.31</td>
<td>60%</td>
<td>9.85</td>
<td>114.80</td>
<td>13.0</td>
<td>12.0</td>
<td>10.5</td>
<td>9.8</td>
<td>7.6</td>
<td>7.6</td>
<td>13.11</td>
<td>13.11</td>
<td>2.53</td>
<td>35.62</td>
<td>1.11</td>
<td>1.59</td>
<td>WATERFALL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>18.0</td>
<td>480.00</td>
<td>30%</td>
<td>4.65</td>
<td>118.69</td>
<td>10.5</td>
<td>9.5</td>
<td>7.5</td>
<td>7.0</td>
<td>5.6</td>
<td>5.6</td>
<td>12.91</td>
<td>12.91</td>
<td>2.54</td>
<td>20.44</td>
<td>0.98</td>
<td>1.40</td>
<td>WATERFALL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>18.2</td>
<td>478.03</td>
<td>10%</td>
<td>1.64</td>
<td>121.15</td>
<td>10.7</td>
<td>10.2</td>
<td>8.0</td>
<td>7.6</td>
<td>6.1</td>
<td>6.1</td>
<td>12.81</td>
<td>12.81</td>
<td>2.52</td>
<td>8.82</td>
<td>0.75</td>
<td>1.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>18.2</td>
<td>230.00</td>
<td>90%</td>
<td>5.75</td>
<td>110.13</td>
<td>11.2</td>
<td>10.5</td>
<td>8.5</td>
<td>8.0</td>
<td>6.2</td>
<td>6.2</td>
<td>6.45</td>
<td>6.45</td>
<td>1.27</td>
<td>49.88</td>
<td>13.2</td>
<td>0.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>36.2</td>
<td>241.27</td>
<td>60%</td>
<td>9.65</td>
<td>111.77</td>
<td>10.4</td>
<td>10.2</td>
<td>8.3</td>
<td>7.9</td>
<td>6.2</td>
<td>6.2</td>
<td>6.49</td>
<td>6.49</td>
<td>1.24</td>
<td>39.05</td>
<td>38</td>
<td>0.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>35.8</td>
<td>240.97</td>
<td>30%</td>
<td>4.95</td>
<td>118.86</td>
<td>10.5</td>
<td>9.5</td>
<td>8.0</td>
<td>7.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.48</td>
<td>6.48</td>
<td>1.24</td>
<td>20.47</td>
<td>60</td>
<td>0.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>35.9</td>
<td>240.87</td>
<td>90%</td>
<td>6.75</td>
<td>112.98</td>
<td>11.0</td>
<td>10.5</td>
<td>8.5</td>
<td>7.6</td>
<td>7.6</td>
<td>7.6</td>
<td>3.01</td>
<td>3.01</td>
<td>0.93</td>
<td>57.12</td>
<td>0</td>
<td>0</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**SEPARATOR TYPE: Echometer 2**

OD DIP TUBE = 1.5"
NUMBER OF ANCHOR PORTS = 4
DIMENSIONS OF THE ANCHOR PORTS = 2" x 4"
FLUID ENTERING BELOW THE ANCHOR PORTS
\( P_c = 10 \text{ psi} \)

**Figure 5-65**

- **Superficial Liquid Velocity inside Separator (in/sec)**
- **Superficial Gas Velocity in casing annulus (in/sec)**
- **Gas Rate through Separator (MSCF/day)**
Increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate flowing through the separator.

In Figure 5-65, it is noticed that when the liquid velocity is between 12.81 and 13.11 inches/second, the gas rate in separator increases from 1.08 MSCFD to 1.71 MSCFD (liquid trend curve). Figure 5-66 (Tests 1, 2, 3 and 4 for Echometer 2) shows these differences. The waterfall phenomenon was observed in Tests 1 and 2 for Echometer 2 and Test 1 for Echometer 1 (Figure 5-66).

When the liquid velocity is between 6.43 to 6.48 inches/second, the gas rate in separator increases from 0.359 MSCFD to 0.790 MSCFD (Figure 5-63, Tests 5, 6 and 7 for Echometer 2).

When the liquid velocity is 3.01 inches/second and the gas velocity is 57.12 inches/second, the gas rate in separator is almost 0.0 (Figure 5-66, Test 8 for Echometer 2).

In Figure 5-66, the pictures are shown side by side to compare the tests under the same conditions for Echometer 1 and Echometer 2.

**Figure 5-66: Echometer 1 vs. Echometer 2 (Fluid entering below the anchor ports at \( P_c = 10 \) psi)**

<table>
<thead>
<tr>
<th>Test 1 Echometer 1</th>
<th>Test 1 Echometer 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(VL= 11.79 inch/se, VG= 51.11 inch/sec)</td>
<td>(VL= 12.97 inch/se, VG= 51.93 inch/sec)</td>
</tr>
</tbody>
</table>
Figure 5-66 – continued

Test 2 Echometer 1
(VL= 11.78 inch/se, VG= 39.22 inch/sec)

Test 2 Echometer 2
(VL= 13.11 inch/se, VG= 35.62 inch/sec)

Test 3 Echometer 1
(VL= 12.04 inch/se, VG= 20.28 inch/sec)

Test 3 Echometer 2
(VL= 12.91 inch/se, VG= 20.44 inch/sec)

Test 4 Echometer 1
(VL= 11.94 inch/se, VG= 6.89 inch/sec)

Test 4 Echometer 2
(VL= 12.81 inch/se, VG= 6.82 inch/sec)
Figure 5-66 – continued

Test 5 Echometer 1
(VL = 5.99 inch/sec, VG = 57.69 inch/sec)

Test 5 Echometer 2
(VL = 6.43 inch/sec, VG = 55.68 inch/sec)

Test 6 Echometer 1
(VL = 5.95 inch/sec, VG = 38.50 inch/sec)

Test 6 Echometer 2
(VL = 6.49 inch/sec, VG = 38.00 inch/sec)

Test 7 Echometer 1
(VL = 5.99 inch/sec, VG = 20.06 inch/sec)

Test 7 Echometer 2
(VL = 6.48 inch/sec, VG = 20.47 inch/sec)
5.3.4 Analysis of the effect of Dip Tube Diameter on the performance of the Echometer Models

Echometer models have the same behavior of Patterson models. By increasing the dip tube diameter, the gas rate in separator increases at the same liquid velocity. This is independently of the position (fluid is entering in front or below the anchor ports); the volume of gas is increased in almost 1.2 times (Figures 5-67 and 5-68).

When the fluid is entering in front the anchor ports, as in the case of Echometer 2 (2” x 4” & dip tube = 1.5”), the pressure drop in the system is almost constant (straight line), with a maximum value of 1.2 psi and a minimum value of 1.0 psi (Figure 5-69).

In the case of Echometer 1 (2” x 4” & dip tube = 1”), the pressure drop increases considerably with the liquid rate, the maximum value is 5.0 psi and the minimum value is 1.3 psi (Figure 5-70).

When the fluid is entering below the anchor ports, as in the case of Echometer 2, the pressure drop in the system has a 1.4 psi as a maximum value and 0.9 psi as a minimum value (Figure 5-71).

In the case of Echometer 1, the pressure drop increases considerably with the liquid rate, the maximum value is 4.8 psi and the minimum value is 1.5 psi (Figure 5-72).
Tables 5-22 and 5-23 show the calculation of P2. Figures 5-73 and 5-74 show P2 calculated vs. P2 measured for Echometer 2 and Echometer 1, respectively. On these graphs, a 45° line was plotted to see the difference between the calculated and measured values. It is observed that the calculated and measured values are very similar; therefore, in the field we can calculate the P2.
Figure 5-67

ECHOMETER 1 VS ECHOMETER 2
FLUID ENTERING IN FRONT THE SLOTS @ 10 psi
Figure 5-68

ECHOMETER 1 VS ECHOMTER 2
FLUID ENTERING BELOW THE SLOTS @ 10 psi
**Figure 5-69**

**SEPARATOR TYPE: Echometer 2**

Fluid entering in front the anchor ports

100 % WATER

<table>
<thead>
<tr>
<th>Floco Meter (sec/0.1BBl)</th>
<th>Q (bbd)</th>
<th>Pc (psi)</th>
<th>P1 (psi)</th>
<th>P2 (psi Hg)</th>
<th>Delta P (P1-P2) (psi)</th>
<th>P2 (calculated) (psi)</th>
<th>Delta P (P1-P2) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.82</td>
<td>673.95</td>
<td>10.2</td>
<td>7</td>
<td>5.8</td>
<td>1.2</td>
<td>5.72</td>
<td>1.3</td>
</tr>
<tr>
<td>13.12</td>
<td>658.54</td>
<td>10.3</td>
<td>7.1</td>
<td>5.9</td>
<td>1.2</td>
<td>5.84</td>
<td>1.3</td>
</tr>
<tr>
<td>15.23</td>
<td>567.30</td>
<td>10.1</td>
<td>6.9</td>
<td>5.7</td>
<td>1.2</td>
<td>5.73</td>
<td>1.2</td>
</tr>
<tr>
<td>24.51</td>
<td>352.51</td>
<td>10.1</td>
<td>6.9</td>
<td>5.8</td>
<td>1.1</td>
<td>5.91</td>
<td>1.0</td>
</tr>
<tr>
<td>37.28</td>
<td>231.76</td>
<td>10.1</td>
<td>6.9</td>
<td>5.9</td>
<td>1.0</td>
<td>5.97</td>
<td>0.9</td>
</tr>
<tr>
<td>82.54</td>
<td>104.68</td>
<td>10.1</td>
<td>7.1</td>
<td>6.0</td>
<td>1.1</td>
<td>6.22</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**Delta P vs Rate**

\[ y = 0.0003x + 1.01 \]

\[ y = 0.8011e^{0.0007x} \]

\[ R^2 = 0.6903 \]

\[ R^2 = 0.9882 \]
Figure 5-70

SEPARATOR TYPE: Echometer 1
Fluid entering in front the anchor ports
100 % WATER

<table>
<thead>
<tr>
<th>Floco Meter (sec/ 0.1Bbl)</th>
<th>Q (bbd)</th>
<th>Pc (psi)</th>
<th>P1 (psi)</th>
<th>P2 (psi)</th>
<th>Delta P (P1-P2) (psi)</th>
<th>Delta P (P1-P2) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.30</td>
<td>702.44</td>
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<td>7.8</td>
<td>2.8</td>
<td>5.0</td>
<td>1.87</td>
</tr>
<tr>
<td>12.99</td>
<td>665.13</td>
<td>9.8</td>
<td>7.6</td>
<td>2.5</td>
<td>4.5</td>
<td>1.55</td>
</tr>
<tr>
<td>14.67</td>
<td>588.96</td>
<td>9.9</td>
<td>7.2</td>
<td>2.6</td>
<td>4.6</td>
<td>2.66</td>
</tr>
<tr>
<td>18.25</td>
<td>473.42</td>
<td>10.7</td>
<td>7.3</td>
<td>3.8</td>
<td>3.5</td>
<td>3.96</td>
</tr>
<tr>
<td>29.06</td>
<td>297.32</td>
<td>10.7</td>
<td>8.1</td>
<td>5.6</td>
<td>2.5</td>
<td>6.16</td>
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<td>31.42</td>
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<td>2.8</td>
<td>6.20</td>
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<tr>
<td>55.24</td>
<td>156.41</td>
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<td>7.3</td>
<td>6.0</td>
<td>1.3</td>
<td>6.09</td>
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</tbody>
</table>

SEPARATOR TYPE: Echometer 1
Fluid entering in front the anchor ports
100 % WATER

Delta P vs Rate

\[ y = 0.8043e^{0.0029x} \]

\[ R^2 = 0.9967 \]

\[ y = 0.0062x + 0.6692 \]

\[ R^2 = 0.9563 \]
**Figure 5-71**

**SEPARATOR TYPE: Echometer 2**

Fluid entering below the anchor ports

100 % WATER

<table>
<thead>
<tr>
<th>Floco Meter (sec/0.1BBl)</th>
<th>Q (bbd)</th>
<th>Pc (psi)</th>
<th>P1 (psi)</th>
<th>P2 (psi)</th>
<th>Delta P (P1-P2) (psi)</th>
<th>Delta P (P1-P2) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.36</td>
<td>646.71</td>
<td>10.0</td>
<td>6.8</td>
<td>5.4</td>
<td>1.4</td>
<td>5.55</td>
</tr>
<tr>
<td>14.36</td>
<td>601.67</td>
<td>10.0</td>
<td>6.9</td>
<td>5.6</td>
<td>1.3</td>
<td>5.70</td>
</tr>
<tr>
<td>16.30</td>
<td>530.06</td>
<td>10.0</td>
<td>6.9</td>
<td>5.7</td>
<td>1.2</td>
<td>5.77</td>
</tr>
<tr>
<td>23.25</td>
<td>371.61</td>
<td>10.1</td>
<td>7.0</td>
<td>5.9</td>
<td>1.1</td>
<td>5.99</td>
</tr>
<tr>
<td>35.48</td>
<td>243.52</td>
<td>10.1</td>
<td>6.9</td>
<td>5.9</td>
<td>1.0</td>
<td>5.97</td>
</tr>
<tr>
<td>68.67</td>
<td>125.82</td>
<td>10.0</td>
<td>6.8</td>
<td>5.9</td>
<td>0.9</td>
<td>5.91</td>
</tr>
</tbody>
</table>

**Delta P vs Rate**

\[ y = 0.0009x + 0.778 \]
\[ R^2 = 0.9714 \]

\[ y = 0.7993e^{0.0007x} \]
\[ R^2 = 0.9891 \]
Figure 5-72

SEPARATOR TYPE: Echometer 1
Fluid entering below the anchor ports
100 % WATER

<table>
<thead>
<tr>
<th>Floco Meter (sec/0.1BBI)</th>
<th>Q (bbd)</th>
<th>Pc (psi)</th>
<th>P1 (psi)</th>
<th>P2 (psi)</th>
<th>( \Delta P ) (psi)</th>
<th>P2 (calculated) (psi)</th>
<th>( \Delta P ) (P1-P2) (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.11</td>
<td>659.04</td>
<td>10.3</td>
<td>7.7</td>
<td>3.0</td>
<td>4.7</td>
<td>2.33</td>
<td>5.4</td>
</tr>
<tr>
<td>13.81</td>
<td>625.63</td>
<td>10.2</td>
<td>7.6</td>
<td>2.8</td>
<td>4.8</td>
<td>2.63</td>
<td>5.0</td>
</tr>
<tr>
<td>15.53</td>
<td>556.34</td>
<td>9.4</td>
<td>6.7</td>
<td>2.2</td>
<td>4.5</td>
<td>2.52</td>
<td>4.2</td>
</tr>
<tr>
<td>23.07</td>
<td>374.51</td>
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<td>7.4</td>
<td>4.4</td>
<td>3.0</td>
<td>4.91</td>
<td>2.5</td>
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<tr>
<td>36.90</td>
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<td>5.9</td>
<td>1.7</td>
<td>6.03</td>
<td>1.6</td>
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<td>81.82</td>
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<td>1.5</td>
<td>6.46</td>
<td>1.0</td>
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</tbody>
</table>

Delta P vs Rate

\[ y = 0.7805e^{0.003x} \]
\[ R^2 = 0.998 \]

\[ y = 0.0066x + 0.5395 \]
\[ R^2 = 0.9694 \]
Table 5-22: Calculation of P2 for Echometer 1

<table>
<thead>
<tr>
<th>Qtestrate (bbd)</th>
<th>Vejorrate (m/s)</th>
<th>P1 (psl)</th>
<th>Rediptube/a-chor</th>
<th>ffactordiptube anchor</th>
<th>P4 (psl)</th>
<th>Vdiptube</th>
<th>Rediptube</th>
<th>ffactordiptube anchor</th>
<th>Vtubing</th>
<th>Retubing</th>
<th>ffactortubing</th>
<th>1/2 ρ△V^2 (psl)</th>
<th>P3 (psl)</th>
<th>P2 (calculated)</th>
<th>P2 (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>702</td>
<td>0.3912</td>
<td>7.8</td>
<td>6974</td>
<td>0.0085</td>
<td>9.7535</td>
<td>4.5639</td>
<td>11910</td>
<td>0.00737</td>
<td>0.26714</td>
<td>2881</td>
<td>0.01066</td>
<td>-1.5053</td>
<td>2.51915</td>
<td>1.86799</td>
<td>2.8000</td>
</tr>
<tr>
<td>665</td>
<td>0.3704</td>
<td>7</td>
<td>6603</td>
<td>0.0086</td>
<td>8.9532</td>
<td>4.3215</td>
<td>11277</td>
<td>0.00748</td>
<td>0.25295</td>
<td>2728</td>
<td>0.01115</td>
<td>-1.34965</td>
<td>2.19747</td>
<td>1.54642</td>
<td>2.5000</td>
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<tr>
<td>589</td>
<td>0.3280</td>
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<td>5847</td>
<td>0.0089</td>
<td>9.1525</td>
<td>3.8266</td>
<td>9986</td>
<td>0.00772</td>
<td>0.22398</td>
<td>2416</td>
<td>0.01157</td>
<td>-1.05823</td>
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<td>4700</td>
<td>0.0086</td>
<td>9.2516</td>
<td>3.0759</td>
<td>8027</td>
<td>0.00818</td>
<td>0.18004</td>
<td>1942</td>
<td>0.01239</td>
<td>-0.68378</td>
<td>4.60576</td>
<td>3.95523</td>
<td>3.6000</td>
</tr>
<tr>
<td>297</td>
<td>0.1656</td>
<td>8.1</td>
<td>2952</td>
<td>0.0109</td>
<td>10.0056</td>
<td>1.9317</td>
<td>5041</td>
<td>0.00930</td>
<td>0.11307</td>
<td>1220</td>
<td>0.01442</td>
<td>-0.26968</td>
<td>6.80905</td>
<td>6.15889</td>
<td>5.6000</td>
</tr>
<tr>
<td>275</td>
<td>0.1531</td>
<td>8</td>
<td>2730</td>
<td>0.0111</td>
<td>9.9003</td>
<td>1.7866</td>
<td>4662</td>
<td>0.00951</td>
<td>0.10458</td>
<td>1128</td>
<td>0.01481</td>
<td>-0.23069</td>
<td>6.84888</td>
<td>6.19875</td>
<td>5.2000</td>
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<tr>
<td>156</td>
<td>0.0871</td>
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<td>1553</td>
<td>0.0133</td>
<td>9.2499</td>
<td>1.0162</td>
<td>2652</td>
<td>0.01124</td>
<td>0.05948</td>
<td>642</td>
<td>0.01805</td>
<td>-0.07543</td>
<td>6.73963</td>
<td>6.08968</td>
<td>6.0000</td>
</tr>
</tbody>
</table>

IN FRONT THE PERFORATIONS

BELOW THE PERFORATIONS

Table 5-23: Calculation of P2 for Echometer 2

<table>
<thead>
<tr>
<th>Qtestrate (bbd)</th>
<th>Vejorrate (m/s)</th>
<th>P1 (psl)</th>
<th>Rediptube/a-chor</th>
<th>ffactordiptube anchor</th>
<th>P4 (psl)</th>
<th>Vdiptube</th>
<th>Rediptube</th>
<th>ffactordiptube anchor</th>
<th>Vtubing</th>
<th>Retubing</th>
<th>ffactortubing</th>
<th>1/2 ρ△V^2 (psl)</th>
<th>P3 (psl)</th>
<th>P2 (calculated)</th>
<th>P2 (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>674</td>
<td>0.4836</td>
<td>7</td>
<td>7867</td>
<td>0.0082</td>
<td>8.9556</td>
<td>1.5031</td>
<td>7082</td>
<td>0.00846</td>
<td>0.25630</td>
<td>2925</td>
<td>0.01091</td>
<td>-0.15908</td>
<td>6.37036</td>
<td>5.71930</td>
<td>5.8000</td>
</tr>
<tr>
<td>659</td>
<td>0.4530</td>
<td>7.1</td>
<td>7688</td>
<td>0.0083</td>
<td>9.0563</td>
<td>1.4887</td>
<td>6920</td>
<td>0.00852</td>
<td>0.25044</td>
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<td>0.01099</td>
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<tr>
<td>567</td>
<td>0.3903</td>
<td>6.9</td>
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<td>0.0086</td>
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<td>1.2652</td>
<td>5962</td>
<td>0.00887</td>
<td>0.21574</td>
<td>2462</td>
<td>0.01150</td>
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<td>5115</td>
<td>0.0099</td>
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<td>0.7882</td>
<td>3704</td>
<td>0.01017</td>
<td>0.13406</td>
<td>1630</td>
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<tr>
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<td>0.0112</td>
<td>8.8505</td>
<td>0.5169</td>
<td>2436</td>
<td>0.01154</td>
<td>0.08814</td>
<td>1026</td>
<td>0.01540</td>
<td>-0.01881</td>
<td>6.62616</td>
<td>5.97356</td>
<td>5.9000</td>
</tr>
<tr>
<td>105</td>
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<td>1222</td>
<td>0.0144</td>
<td>9.0498</td>
<td>0.2335</td>
<td>1100</td>
<td>0.01494</td>
<td>0.03981</td>
<td>454</td>
<td>0.02092</td>
<td>-0.03849</td>
<td>6.86873</td>
<td>6.21883</td>
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</tr>
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<td>647</td>
<td>0.4449</td>
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<td>7549</td>
<td>0.0083</td>
<td>8.7551</td>
<td>1.4923</td>
<td>6796</td>
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<tr>
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<td>7024</td>
<td>0.0085</td>
<td>8.8545</td>
<td>1.3419</td>
<td>6323</td>
<td>0.00873</td>
<td>0.22882</td>
<td>2611</td>
<td>0.01130</td>
<td>-0.12679</td>
<td>6.34178</td>
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<td>5.6000</td>
</tr>
<tr>
<td>372</td>
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<td>4338</td>
<td>0.0097</td>
<td>8.9517</td>
<td>0.8288</td>
<td>3995</td>
<td>0.01001</td>
<td>0.14132</td>
<td>1613</td>
<td>0.01315</td>
<td>-0.04837</td>
<td>6.64365</td>
<td>5.99326</td>
<td>5.9000</td>
</tr>
<tr>
<td>244</td>
<td>0.1675</td>
<td>6.9</td>
<td>2843</td>
<td>0.0110</td>
<td>8.9506</td>
<td>0.5431</td>
<td>2559</td>
<td>0.01137</td>
<td>0.06261</td>
<td>1057</td>
<td>0.01514</td>
<td>-0.02077</td>
<td>6.61808</td>
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<tr>
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<td>1469</td>
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<td>8.7495</td>
<td>0.2866</td>
<td>1322</td>
<td>0.01404</td>
<td>0.04785</td>
<td>546</td>
<td>0.01915</td>
<td>-0.00554</td>
<td>6.56315</td>
<td>5.91323</td>
<td>5.9000</td>
</tr>
</tbody>
</table>

IN FRONT THE PERFORATIONS

BELOW THE PERFORATIONS
Figure 5-73

P2 calculated vs P2 Measured
SEPARATOR TYPE: Echometer 1
(100 % WATER)
Pc=5 & 10 psi
Figure 5-74

P2 calculated vs P2 Measured
SEPARATOR TYPE: Echometer 2
(100% WATER)
Pc=5 & 10 psi

P2 Calculated (psi) vs P2 Measured (psi)

- 5 psi (in front ports)
- 10 psi (in front ports)
- 45° line
- 5 psi (below ports)
- 10 psi (below ports)
**Pressure Drop**

Figure 5-75 and 5-76 shows the pressure drop for all the separator models with 1” OD diameter and when the fluid is entering in front and below the anchor ports, respectively. It is noticed that independent on the model, the pressure drop have the same magnitude for all the separators models.

Figure 5-77 and 5-78 shows the pressure drop for all the separator models with 1.5” OD diameter and when the fluid is entering in front and below the anchor ports, respectively. It is noticed that independent on the model, the pressure drop have the same magnitude for all the separators models.

Therefore, independently of the model (Patterson, Echometer of Bucket) or the position of the anchor ports (fluid entering in front, below of above the anchor ports), the pressure drop depends directly on the dip tube diameter. A large dip tube diameter, the pressure drop is low; a small dip tube diameter the pressure drop is high. However, on the other hand, a large dip tube diameter, the gas rate going through the separator is greater than for a small dip tube diameter.

The optimum dip tube diameter will be the largest diameter that is permitted (this depends on the diameter of the casing and of the separator).
Figure 5-75

**Delta P vs Rate**

FLUID ENTERING IN FRONT THE SLOTS

DIP TUBE DIAMETER = 1”

*Echometer 1 Measured*
*Echometer 1 Calculated*
*Echometer 3 Measured*
*Echometer 3 Calculated*
*Patterson 2 Measured*
*Patterson 2 Calculated*
*Patterson 3 Measured*
*Patterson 3 Calculated*
*Patterson 4 Measured*
*Patterson 4 Calculated*
*Patterson 7 Measured*
*Patterson 7 Calculated*
Figure 5-76

Delta P vs Rate
FLUID ENTERING BELOW THE SLOTS
DIP TUBE DIAMETER = 1"

<table>
<thead>
<tr>
<th>Measured</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echometer 1</td>
<td>Echometer 1</td>
</tr>
<tr>
<td>Echometer 3</td>
<td>Echometer 3</td>
</tr>
<tr>
<td>Patterson 2</td>
<td>Patterson 2</td>
</tr>
<tr>
<td>Patterson 3</td>
<td>Patterson 3</td>
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<tr>
<td>Patterson 4</td>
<td>Patterson 4</td>
</tr>
<tr>
<td>Patterson 7</td>
<td>Patterson 7</td>
</tr>
</tbody>
</table>
Figure 5-77

Delta P vs Rate
FLUID ENTERING IN FRONT THE SLOTS
DIP TUBE DIAMETER = 1.5"

Bucket Measured
Bucket Calculated
Echometer 2 Measured
Echometer 2 Calculated
Patterson 5 Measured
Patterson 5 Calculated
Patterson 6 Measured
Patterson 6 Calculated
Figure 5-78

**Delta P vs Rate**

FLUID ENTERING BELOW THE SLOTS

DIP TUBE DIAMETER = 1.5"

- Bucket Measured
- Bucket Calculated
- Echometer 2 Measured
- Echometer 2 Calculated
- Patterson 5 Measured
- Patterson 5 Calculated
- Patterson 6 Measured
- Patterson 6 Calculated

**Q (bbd)**

**Delta P (psi)**

Calculated
Measured
5.4 Pressure Effect

The downhole gas separators were tested at two different casing pressures (Pc): 5 and 10 psi. These tests were repeated for each of the separator models with fluid entering the anchor ports at three different positions:

1. Fluid entering from above the anchor ports
2. Fluid entering in front the anchor ports
3. Fluid entering below the anchor ports

5.4.1 Patterson Models

The Patterson 4 model (anchor ports = 8” x 3/4” & dip tube = 1”) was chosen to be used for the discussion of the pressure effect because all the Patterson models have the same response to the pressure effect.

Figure 5-30 (5-30a and 5-30b) shows the Patterson 4 model. It is observed in the pictures that Patterson 4 has eight anchor ports. Each anchor port is 8 inches long and 3/4 inches wide. The dip tube is 1 inch OD and 3/4 inches ID. The characteristics of the geometry of this separator are detailed in Figure 5-31.

Fluid Entering in Front the Anchor Ports

Table 5-24 shows the data obtained from the test and the data calculated for Patterson 4 when the fluid is entering in front the anchor ports and the casing pressures are 5 and 10 psi.
Table 5-24

| Test N° | Floco Meter | Liquid Rate | Gas Rate BBD | Gas Rate MCF | Gas Rate Pressure | Gas Rate Maximum | Gas Rate Minimum | Ports Pressure | Ports Maximum | Ports Minimum | Annulus Pressure | Annulus Maximum | Annulus Minimum | Tubing Pressure | Tubing Maximum | Tubing Minimum | Superficial Liquid Velocity in Separator | Superficial Liquid Velocity in Casing | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Gas Rate through Separator | Comments |
|---------|-------------|-------------|--------------|--------------|------------------|------------------|-----------------|---------------|---------------|---------------|-----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|--------------------------------|--------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|--------|
| 1       | 12.1        | 714.05      | 90% 14.78    | 108.40       | 109.02           | 6.0             | 4.8             | 3.8           | 2.0           | -5.5          | -6.0            | 15.53           | 3.11            | 70.25           | 65             | 0.029          | FL-3820C 38 cm | FL-3830ST 37 cm | FL-5000 SCFM | MSCF            | PPSF          | FL-5000 SCFM | MSCF            | 0.009  |
| 2       | 12.8        | 687.35      | 60% 9.88     | 110.50       | 74.10            | 6.0             | 4.5             | 3.3           | 1.8           | -5.5          | -6.0            | 14.98           | 3.64            | 45              | 55             | 0.024          | FL-3820C 38 cm | FL-3830ST 37 cm | FL-5000 SCFM | MSCF            | PPSF          | FL-5000 SCFM | MSCF            | 0.019  |
| 3       | 12.0        | 702.44      | 30% 4.93     | 118.77       | 39.81            | 6.0             | 4.5             | 3.0           | 1.5           | -6.0          | -6.5            | 15.31           | 3.72            | 35              | 43             | 0.007          | FL-3820C 38 cm | FL-3830ST 37 cm | FL-5000 SCFM | MSCF            | PPSF          | FL-5000 SCFM | MSCF            | 0.007  |
| 4       | 12.4        | 809.60      | 10% 1.04     | 119.69       | 13.35            | 6.0             | 4.5             | 2.5           | 2.0           | -5.0          | -5.6            | 15.25           | 3.71            | 15              | 15             | 0.007          | FL-3820C 38 cm | FL-3830ST 37 cm | FL-5000 SCFM | MSCF            | PPSF          | FL-5000 SCFM | MSCF            | 0.007  |
| 5       | 11.5        | 598.74      | 90% 14.78    | 110.61       | 120.23           | 6.0             | 4.5             | 3.5           | 2.5           | -2.0          | -2.0            | 12.17           | 2.96            | 70              | 80             | 0.005          | FL-3820C 38 cm | FL-3830ST 37 cm | FL-5000 SCFM | MSCF            | PPSF          | FL-5000 SCFM | MSCF            | 0.005  |
| 6       | 10.0        | 279.88      | 90% 14.78    | 113.78       | 114.41           | 6.2             | 4.5             | 3.5           | 2.5           | 1.0           | 1.0             | 6.10            | 1.49            | 73              | 73             | 0.000          | FL-3820C 38 cm | FL-3830ST 37 cm | FL-5000 SCFM | MSCF            | PPSF          | FL-5000 SCFM | MSCF            | 0.000  |

SEPARATOR TYPE: Patterson 4
OD DIP TUBE=1"
NUMBER OF SLOTS=8
DIMENSIONS OF THE SLOTS=8” x 3/4”
FLUID ENTERING IN FRONT THE ANCHOR PORTS

Date 8/16/2004
PATTERSON 4: FLUID ENTERING IN FRONT THE SLOTS @ 5 & 10 psi
Increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate flowing through the separator.

In Figure 5-79 (Pc= 5psi), it is noticed that when the liquid velocity is between 14.98 and 15.57 inches/second, the gas rate in separator increases from 0.007 MSCFD to 0.028 MSCFD. Figure 5-80 (Test 1 @5 psi, Test 2 @5 psi and Test 3 @5 psi) shows this variation of the gas rate in separator.

It is observed in Figure 5-79 (Pc=5psi) that, when the liquid velocity is 12.17 inches/second, the gas rate in separator is almost 0 MSCFD and when the liquid velocity is 6.10 inches/second, the gas rate in separator is 0 MSCFD (Figure 5-80, Tests 5 @5 psi).

Section 5.2 (Effect of Anchor Port Width on Separator Efficiency) shows the analysis when Pc= 10 psi (Figures 5-36 and 5-37).

In Figure 5-80, the pictures are shown side by side to compare visually the separator performance for Pc= 5 and 10 psi. The title of each picture includes the test number, the casing pressure, the liquid velocity (VL) and the gas velocity (VG).

Figure 5-80: Patterson 4 (5 vs. 10 psi)

Test 1 @ 5 psi  
(VL= 15.57 inch/se, VG= 70.25 inch/sec)  
Test 1 @ 10 psi  
(VL= 15.06 inch/se, VG= 55.47 inch/sec)
Figure 5-80 continued

Test 2 @ 5 psi
(VL= 14.98 inch/se, VG= 48.15 inch/sec)  
Test 2 @ 10 psi
(VL= 15.39 inch/se, VG= 38.53 inch/sec)

Test 3 @ 5 psi
(VL= 15.31 inch/se, VG= 25.87 inch/sec)  
Test 3 @ 10 psi
(VL= 15.31 inch/se, VG= 19.88 inch/sec)

Test 5 @ 5 psi
(VL= 12.17 inch/se, VG= 70.65 inch/sec)  
Test 4 @ 10 psi
(VL= 12.39 inch/se, VG= 55.67 inch/sec)
Figure 5-80 continued

Test 6 @ 5 psi
(VL = 6.10 inch/sec, VG = 73.32 inch/sec)

Test 5 @ 10 psi
(VL = 6.04 inch/sec, VG = 55.09 inch/sec)

Fluid Entering Below the Anchor Ports

Table 5-25 shows the data obtained from the test and the data calculated for the
Patterson 4 separator when the fluid is entering below the anchor ports and the casing
pressures are 5 and 10 psi.
### Table 5-25

**SEPARATOR TYPE:** Patterson 4  
**OD DIP TUBE:** 1"  
**NUMBER OF SLOTS:** 8  
**DIMENSIONS OF THE SLOTS:** 8" x 3/4"  
**FLUID ENTERING BELOW THE ANCHOR PORTS**

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Flood N°</th>
<th>Liquid Rate</th>
<th>Gas meter reading</th>
<th>Gas Rate of</th>
<th>Water Pressure</th>
<th>Gas Rate MSCF</th>
<th>Annulus Pressure Maximum</th>
<th>Annulus Pressure Minimum</th>
<th>Ports Pressure Maximum</th>
<th>Ports Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Tubing Pressure Minimum</th>
<th>Superficial Liquid Velocity in Separator</th>
<th>Superficial Gas Velocity in Casing</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
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<td>21.5</td>
<td>461.97</td>
<td>96%</td>
<td>14.75</td>
<td>103.89</td>
<td>104.24</td>
<td>0.5 0.4 0.5 0.4</td>
<td>1.0 1.0 0.75 2.25 60.00</td>
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<td>2</td>
<td>20.8</td>
<td>416.39</td>
<td>60%</td>
<td>9.86</td>
<td>110.99</td>
<td>74.49</td>
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<td>115.75</td>
<td>38.83</td>
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<td>4</td>
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<td>440.09</td>
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<td>60%</td>
<td>14.75</td>
<td>105.81</td>
<td>108.41</td>
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<td>0.6 0.6 0.53 4.56 68.20</td>
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<td>9.86</td>
<td>110.81</td>
<td>75.94</td>
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<td>7</td>
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<td>14.78</td>
<td>109.90</td>
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<td>0.75</td>
<td>1.08 WATERFALL</td>
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<td>9</td>
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<td>112.53</td>
<td>75.48</td>
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<td>10</td>
<td>15.4</td>
<td>521.78</td>
<td>30%</td>
<td>4.93</td>
<td>117.62</td>
<td>39.50</td>
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<td>11</td>
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<tr>
<td>12</td>
<td>31.1</td>
<td>278.08</td>
<td>96%</td>
<td>14.78</td>
<td>110.82</td>
<td>111.45</td>
<td>10.5 9.8 8.5 7.9</td>
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<td>14</td>
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<td>4.93</td>
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<td>39.81</td>
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<td>15</td>
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<td>109.78</td>
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</tr>
</tbody>
</table>

**Date:** 8/18/2004
Figure 5-81

PATTERSON 4: FLUID ENTERING BELOW THE SLOTS @ 5 & 10 psi
Figure 5-81 (Pc=5psi), shows that when the liquid velocity is between 8.76 and 9.60 inches/second, the gas rate in separator increases from 0.299 MSCFD to 0.550 MSCFD. Figure 5-82 (Tests 1, 2, 3 and 4 @5 psi) shows pictures of the flow in the separator at the entrance of the dip tube.

It is observed in Figure 5-81 that, when the liquid velocity is between 6.11 and 6.12 inches/second, the gas rate in separator increases from 0.191 MSCFD to 0.239 MSCFD. Figure 5-82 (Tests 5 and 6 @5 psi) shows these differences very clearly.

Section 5.2 (Effect of Anchor Port Width on Separator Efficiency) shows the analysis when Pc= 10 psi (Figures 5-42 and 5-43).

**Figure 5-82: Patterson 4 (5 vs. 10 psi)**

<table>
<thead>
<tr>
<th>Test 1 @ 5 psi</th>
<th>Test 1 @ 10 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>(VL= 8.76 inch/se, VG= 65.02 inch/sec)</td>
<td>(VL= 9.13 inch/se, VG= 51.36 inch/sec)</td>
</tr>
<tr>
<td>Test 2 @ 5 psi</td>
<td>Test 2 @ 10 psi</td>
</tr>
<tr>
<td>(VL= 9.08 inch/se, VG= 46.41 inch/sec)</td>
<td>(VL= 9.51 inch/se, VG= 37.14 inch/sec)</td>
</tr>
</tbody>
</table>
Figure 5-82 continued

Test 3 @ 5 psi
(VL= 9.37 inch/se, VG= 23.88 inch/sec)  Test 3 @ 10 psi
(VL= 11.51 inch/se, VG= 19.73 inch/sec)

Test 5 @ 5 psi
(VL= 6.12 inch/se, VG= 68.20 inch/sec)  Test 5 @ 10 psi
(VL= 6.06 inch/se, VG= 56.89 inch/sec)

Test 6 @ 5 psi
(VL= 6.11 inch/se, VG= 45.22 inch/sec)  Test 6 @ 10 psi
(VL= 6.09 inch/se, VG= 37.36 inch/sec)
5.4.2 Analysis of the effect of casing pressure on the performance of the Patterson Models

In Figure 5-79, it is noticed that when the fluid is entering in front the anchor ports and the liquid velocity is between 14.98 and 15.97 inches/second, the gas rate in separator, when Pc=10 psi, is, on average, 1.68 times greater than when the Pc=5 psi.

It is observed in Figure 5-79, when the fluid is entering in front the anchor ports and the liquid velocity are 12.17 (Pc=5 psi) and 12.39 inches/second (Pc=10 psi), the gas rate in separator in both cases is almost 0 MSCFD.

Therefore, the pressure effect is noticed when the liquid velocity is greater than 12.5 inches/second. When the liquid velocity is less than 12.4 inches/second, the gas in separator is almost zero.

In Figure 5-81, it is noticed that when the fluid is entering below the anchor ports and the liquid velocity is between 8.76 and 12.45 inches/second, the gas rate in separator, when Pc=10 psi, is, on average, 1.90 times greater than when the Pc=5 psi.

It is observed in Figure 5-81, when the fluid is entering below the anchor ports and the liquid velocity is between 6.06 and 6.20 inches/second, the gas rate in separator when Pc=10 psi is on average 1.03 times greater than when the Pc=5 psi.
When looking at the pictures (Figure 5-82) and comparing similar tests at different pressures (5 and 10 psi), it is sometimes difficult to distinguish the difference because, in some cases, the gas bubbles look the same. However, that is because one case is at 5 psi and the other one is at 10 psi. When the gas rate through the separator is read at standard conditions, the gas rate at 10 psi will be greater than the gas rate at 5 psi. Figure 5-83 shows this concept.

**Figure 5-83: Pressure effect in the gas bubbles**

Increasing the pressure from 5 psi (19.7 psia) to 10 psi (24.7 psia), the volume of a gas bubble increases 1.25 times \( (P_1V_1= P_2V_2) \), but in the analysis, it is observed that the gas rate going through the separator at 10 psi is 1.90 times greater than at 5 psi. Therefore, there are other factors that influence the increment of the gas rate due to the pressure changes. These factors have not been identified in this study, therefore it is recommended that more detailed studies of the pressure effect be undertaken in the future.
5.4.3 Echometer Models

The Echometer 1 model (4” x 2” & dip tube = 1”) was chosen to be used for the discussion of the pressure effect.

Figure 5-9 (5-9a and 5-9b) shows the Echometer 1 model. It is observed in the pictures that Echometer 1 has four anchor ports. Each anchor port is 4 inches long and 2 inches wide. The dip tube is 1 inch OD and 3/4 inches ID. The characteristics of the geometry of this separator are detailed in Figure 5-10.

Fluid Entering in Front the Anchor Ports

Table 5-26 shows the data obtained from the test and the data calculated for Echometer 1 when the fluid is entering in front the anchor ports and the casing pressures are 5 and 10 psi.
### Table 5-26

**SEPARATOR TYPE:** Echometer 1

**OD DIP TUBE:** 1”

**NUMBER OF SLOTS:** 4

**DIMENSIONS OF THE SLOTS:** 2” x 4”

**FLUID ENTERING IN FRONT THE ANCHOR PORTS**

| Tool No. | Test N° | Test Fl Oz | Liquid Rate | Gas Rate | Gas Rate MCF | Max Annulus Pressure | Min Annulus Pressure | Max Ports Pressure | Min Ports Pressure | Max Tubing Pressure | Min Tubing Pressure | Liquid Velocity in Separator | Gas Velocity in Casing | Max Annulus Pressure (psi) | Min Annulus Pressure (psi) | Max Ports Pressure (psi) | Min Ports Pressure (psi) | Max Tubing Pressure (psi) | Min Tubing Pressure (psi) | Liquid Velocity in Casing (inches/sec) | Gas Velocity in Casing (inches/sec) | Comments |
|----------|---------|------------|-------------|----------|--------------|----------------------|---------------------|--------------------|-------------------|-------------------|-------------------|------------------------------|-------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|-----------------------------|-----------------------------|----------|
|          | 1       | 17.3       | 494.00      | 90%      | 147.36       | 109.81               | 100.00              | 108.68             | 102.80           | 2.84             | 9.04             | 2.4                           | 2.4                      | 10.77                     | 2.62                     | 57.17                     | 150                      | 0.897 WATERFALL (38°)        |
|          | 2       | 17.5       | 493.71      | 60%      | 147.20       | 111.44               | 109.60              | 111.13             | 104.93           | 4.65             | 10.65            | 4.0                           | 4.0                      | 10.53                     | 2.66                     | 19.09                     | 45                       | 0.208 WATERFALL (38°)        |
|          | 3       | 17.5       | 500.15      | 30%      | 145.29       | 110.05               | 108.00              | 110.08             | 98.52            | 6.00             | 8.50             | 4.5                           | 4.5                      | 11.04                     | 2.68                     | 7.02                      | 28                       | 0.165 WATERFALL (38°)        |
|          | 4       | 17.1       | 506.45      | 10%      | 147.20       | 120.93               | 121.51              | 120.93             | 118.55           | 4.50             | 8.50             | 4.5                           | 4.5                      | 8.2                      | 7.8                      | 4.5                       | 4.5                      | 5.25                     | 2.68                     | 7.02                      | 28                       | 0.165 WATERFALL (38°)        |
|          | 5       | 30.1       | 288.08      | 90%      | 147.20       | 108.65               | 108.20              | 108.65             | 8.50             | 4.50             | 8.50             | 4.5                           | 4.5                      | 8.2                      | 8.0                      | 4.5                       | 4.5                      | 8.0                      | 2.68                     | 7.02                      | 28                       | 0.165 WATERFALL (38°)        |
|          | 6       | 20.9       | 288.33      | 60%      | 147.20       | 114.48               | 116.75              | 114.48             | 8.50             | 4.50             | 8.50             | 4.5                           | 4.5                      | 8.2                      | 7.8                      | 4.5                       | 4.5                      | 8.2                      | 2.68                     | 7.02                      | 28                       | 0.165 WATERFALL (38°)        |
|          | 7       | 20.0       | 288.30      | 30%      | 147.20       | 110.05               | 108.00              | 110.08             | 8.50             | 4.50             | 8.50             | 4.5                           | 4.5                      | 8.2                      | 7.8                      | 4.5                       | 4.5                      | 8.2                      | 2.68                     | 7.02                      | 28                       | 0.165 WATERFALL (38°)        |
|          | 8       | 80.8       | 106.98      | 90%      | 147.20       | 110.13               | 110.75              | 110.13             | 8.50             | 4.50             | 8.50             | 4.5                           | 4.5                      | 8.5                      | 7.5                      | 4.5                       | 4.5                      | 8.5                      | 2.68                     | 7.02                      | 28                       | 0.165 WATERFALL (38°)        |
Figure 5-84

ECHOMETER 1: FLUID ENTERING IN FRONT THE SLOTS @ 5 & 10 psi

[Graph showing superficial liquid and gas velocities as variables with data points for fluid entering at 5 and 10 psi.]
Increasing the liquid velocity and/or increasing the gas velocity will increase the gas rate flowing through the separator.

In Figure 5-84 (Pc=5 psi), it is noticed that when the liquid velocity is between 9.72 and 9.78 inches/second, the gas rate in separator increases from 0.041 MSCFD to 0.150 MSCFD. Figure 5-85 (Tests 1, 2, 3 and 4 @ 5 psi) shows this variation of the gas rate in separator. An intermittent waterfall phenomenon was observed in Tests 1 (Figure 5-85 @ 5 psi).

It is observed in Figure 5-84 (Pc=5 psi) that, when the liquid velocity is between 5.97 and 6.03 inches/second, the gas rate in separator increases from 0.005 MSCFD to 0.028 MSCFD. Figure 5-85 (Tests 5, 6 and 7 @ 5 psi) shows these differences very clearly.

Section 5.1 (Position of the Anchor Ports Relative to the Perforations) shows the analysis when Pc= 10 psi (Figures 5-11 and 5-12).

**Figure 5-85: Echometer 1: 5 vs. 10 psi**

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<tr>
<th>Test 1 @ 5 psi</th>
<th>Test 1 @ 10 psi</th>
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<tr>
<td>(VL= 9.72 inch/se, VG= 70.03 inch/sec)</td>
<td>(VL=10.77 inch/se, VG= 57.17 inch/sec)</td>
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</table>
Figure 5-85 continued

Test 2 @ 5 psi  
(VL= 9.88 inch/sec, VG= 50.15 inch/sec)  
Test 2 @ 10 psi  
(VL= 10.76 inch/sec, VG= 38.46 inch/sec)

Test 3 @ 5 psi  
(VL= 9.73 inch/sec, VG= 26.79 inch/sec)  
Test 3 @ 10 psi  
(VL= 10.93 inch/sec, VG= 19.69 inch/sec)

Test 4 @ 5 psi  
(VL= 9.78 inch/sec, VG= 8.89 inch/sec)  
Test 4 @ 10 psi  
(VL= 11.04 inch/sec, VG= 7.02 inch/sec)
Figure 5-85 continued

Test 5 @ 5 psi
(VL= 5.97 inch/sec, VG= 74.13 inch/sec)

Test 5 @ 10 psi
(VL= 6.25 inch/sec, VG= 54.82 inch/sec)

Test 6 @ 5 psi
(VL= 5.98 inch/sec, VG= 49.12 inch/sec)

Test 6 @ 10 psi
(VL= 6.31 inch/sec, VG= 38.59 inch/sec)

Test 7 @ 5 psi
(VL= 6.03 inch/sec, VG= 25.92 inch/sec)

Test 7 @ 10 psi
(VL= 6.28 inch/sec, VG= 20.13 inch/sec)
Fluid Entering below the Anchor ports

Table 5-27 shows the data obtained from the test and the data calculated for Echometer 1 when the fluid is entering below the anchor ports and the casing pressures are 5 and 10 psi.
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Figure 5-86

ECHOMETER 1: FLUID ENTERING BELOW THE SLOTS @ 5 & 10 psi
In Figure 5-86 (Pc=5 psi), it is noticed that when the liquid velocity is between 9.43 and 9.77 inches/second, the gas rate in separator increases from 0.203 MSCFD to 0.377 MSCFD.

It is observed in Figure 5-86 (Pc=5 psi) that, when the liquid velocity is between 6.02 and 6.06 inches/second, the gas rate in separator increases from 0.114 MSCFD to 0.150 MSCFD. Figure 5-87 (Tests 5 and 6 @ 5 psi) shows these differences very clearly.

Section 5.1 (Position of the Anchor Ports Relative to the Perforations) shows the analysis when Pc= 10 psi (Figures 5-13 and 5-14).

In Figure 5-87, the pictures are presented side by side to compare the tests for Pc= 5 and 10 psi. The title of each picture includes the test number, the casing pressure, the liquid velocity (VL) and the gas velocity (VG).

Figure 5-87: Echometer 1 (5 vs. 10 psi)

Test 5 @ 5 psi
(VL= 6.12 inch/se, VG= 68.20 inch/sec)

Test 5 @ 10 psi
(VL= 6.06 inch/se, VG= 56.89 inch/sec)
5.4.4 Analysis of the effect of casing pressure on the performance of the Echometer Models

In Figure 5-84, it is noticed that when the fluid is entering in front the anchor ports and the liquid velocity is between 9.72 and 11.04 inches/second, the gas rate in separator, when Pc=10 psi, is, on average, 4.7 times greater than when Pc=5 psi. It is observed in Figure 5-84, when the fluid is entering in front the anchor ports and the liquid velocity is between 5.97 and 6.31 inches/second, the gas rate in separator, when Pc=5 psi, is, on average, 5 times greater than when Pc=10 psi. This behavior represents the
opposite of what occurs when the liquid velocity is between 9.72 and 11.04 inches/second.

In Figure 5-86, it is noticed that when the fluid is entering below the anchor ports and the liquid velocity is between 9.43 and 12.04 inches/second, the gas rate in separator, when \( P_c = 10 \) psi, is, on average, 3.33 times greater than when the \( P_c = 5 \) psi.

It is observed in Figure 5-86, when the fluid is entering below the anchor ports and the liquid velocity is between 5.95 and 6.06 inches/second, the gas rate in separator, when \( P_c = 10 \) psi, is, on average 4.19 times greater than when the \( P_c = 5 \) psi.

From Figures 5-80 and 5-82, it is concluded that the liquid velocity value for design when the fluid is entering in front and below the anchor ports is 2 inches/second in both cases (\( P_c = 5 \) and 10 psi).

Comparing Patterson and Echometer models, the pressure effect is more noticeable in the Echometer models than in the Patterson models; increasing 5 psi (from 5 to 10 psi) in the Echometer models will result in more gas in separator than in the Patterson models.

Therefore, independent of the model (Patterson or Echometer), by only changing the casing pressure from 5 to 10 psi, under the same conditions (position of the anchor ports, liquid and gas velocity), the gas in separator will be greater. The exception is when the fluid is entering in front the anchor ports and the liquid velocity is between 5.97 and 6.31 inches/second. In this case, the gas rate in separator for \( P_c = 5 \) psi is, on average, 5 times greater than for \( P_c = 10 \) psi, but in this situation because the gas rates are very small, this could be due to an error in measurement.

In the field, increasing or decreasing the casing pressure opposite the separator entry ports can be made either by increasing or decreasing the fluid flow rate or by lowering or raising the separator relative to the perforations when producing at a constant rate.

As with the Patterson model, looking at the pictures and comparing similar tests at different pressures (5 and 10 psi), sometimes it is difficult to see the difference in the quantities of gas. Again, this is because, in some cases, the gas bubbles look the same,
but that is because in one case the casing pressure is 5 psi and in the other is 10 psi. When the gas rate through the separator is read at standard conditions, the gas rate at 10 psi will be greater than the gas rate at 5 psi. Figure 5-83 shows this concept.

5.5 Visual Observations

A transparent casing was used to run these test. Therefore, the analysis is not only based on measured values; visual observations are as important as measured data.

5.5.1 Flow Path

Special tests were run to observe the flow path in the downhole gas separators. These tests were made with 100 % water flowing through the perforations and injecting small air bubbles below the anchor through a separate gas line to act as tracers to observe the flow path of the liquid in the annulus and inside the separator.

It was noticed that when the liquid is injected through the perforations above the anchor ports, the majority of the liquid enters the separator through the bottom anchor ports. The liquid that is below the bottom anchor port is static while the fluid coming from the perforations above the anchor ports flows to the bottom anchor ports. Almost no liquid flows into the separator through the top anchor ports. As shown in Figure 5-88.

It was also observed that when the liquid is injected through the perforations below the anchor ports, the majority of the liquid enters the separator through the bottom anchor ports. This is the same as the case when the fluid is injected above the anchor ports (Figure 5-89); almost no liquid is flowing into the separator through the top anchor ports.

This behavior was observed in all the downhole gas separator models tested in this project (Patterson, Echometer models).

The conclusion drawn from these observations was that the performance of the Patterson and Echometer separator should not be affected if the upper set of anchor ports were not open. Therefore, two separators were tested (Patterson and Echometer) with the
top anchor ports closed and analyze to determine if the behavior of the separator changes when the top anchor ports are closed.

Figure 5-88: Flow Path (Fluid entering above the anchor ports)
Figure 5-89: Flow Path (Fluid entering below the anchor ports)
5.5.1.1 Performance of the Patterson Models with One Row of Anchor ports

In the case of the Patterson models, Patterson 7 (anchor ports = 8” x 3/4” & dip tube = 1”) was chosen to be used to study the effect of the fluid flow path.

Patterson 7 has the same geometry as Patterson 4 (anchor ports = 8” x 3/4” & dip tube = 1”) but with the top anchor ports closed.

Figure 5-90 (5-90a and 5-90b) shows Patterson 4 and Patterson 7. It is observed in the picture that Patterson 7 has four opened anchor ports. Each anchor port is 8 inches long and 3/4 inches wide. The dip tube is 1 inch OD and 3/4 inches ID. The characteristics of the geometry of this separator are detailed in Figure 5-91.

**Figure 5-90: Patterson 4 and Patterson 7**

![Figure 5-90a: Patterson 4](image1)

![Figure 5-90b: Patterson 7](image2)

**Upper anchor ports closed with clear tape**

**Fluid Entering in Front of the Anchor Ports**

Tables 5-14 and 5-28 show the data obtained from the test and the data calculated for Patterson 4 and 7, respectively, when the fluid is entering in front the anchor ports and the casing pressure is 10 psi.
### GAS ANCHOR

<p>| | | |</p>
<table>
<thead>
<tr>
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<td>inches</td>
</tr>
<tr>
<td>ID</td>
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<td>inches</td>
</tr>
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<tr>
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### HOLES

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<tr>
<td>ID</td>
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<td>inches</td>
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<tr>
<td>Area of each hole</td>
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<td></td>
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<tr>
<td></td>
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### ANCHOR PORTS

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<tr>
<td>Longitude</td>
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</tr>
<tr>
<td>Width</td>
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<td>inches</td>
</tr>
<tr>
<td>Area of each slot</td>
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<td>inch^2</td>
</tr>
<tr>
<td></td>
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<tr>
<td>Total Area</td>
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### DIP TUBE INSIDE THE ANCHOR

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<tr>
<td>ID</td>
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<td>inches</td>
</tr>
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<td>OD Area</td>
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<td>inch^2</td>
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<td>0.005</td>
<td>ft^2</td>
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<tr>
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<td></td>
<td>0.003</td>
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</tbody>
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### CASING

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<td></td>
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</table>

### ANNULAR AREA

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<td>Casing-Anchor</td>
<td>21.206</td>
<td>inch^2</td>
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<tr>
<td></td>
<td>0.147</td>
<td>ft^2</td>
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</table>
**Table 5-28**

**SEPARATOR TYPE:** Patterson 7

**GO DIP TUBE:** 1"

**NUMBER OF SLOTS:** 4

**DIMENSIONS OF THE SLOTS:** 3/4" x 3/4"

**FLUID ENTERING IN FRONT THE ANCHOR PORTS**

<table>
<thead>
<tr>
<th>Test N°</th>
<th>Floco Meter</th>
<th>Liquid Rate</th>
<th>Gas Rate reading</th>
<th>Gas Rate MCF</th>
<th>Gas Rate Pressure</th>
<th>Gas Rate Pressure Maximum</th>
<th>Ammulus Pressure Maximum</th>
<th>Ports Pressure Minimum</th>
<th>Tubing Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Liquid Velocity in Separator</th>
<th>Gas Rate in Casing</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.6</td>
<td>679.00</td>
<td>90%</td>
<td>14.78</td>
<td>107.25</td>
<td>58.37</td>
<td>11.0</td>
<td>10.0</td>
<td>9.5</td>
<td>7.3</td>
<td>3.0</td>
<td>2.5</td>
<td>64.65</td>
<td>36.45</td>
<td>108.31</td>
</tr>
<tr>
<td>2</td>
<td>12.7</td>
<td>679.79</td>
<td>90%</td>
<td>14.78</td>
<td>112.12</td>
<td>75.11</td>
<td>11.6</td>
<td>10.0</td>
<td>9.5</td>
<td>7.3</td>
<td>3.0</td>
<td>2.5</td>
<td>64.35</td>
<td>36.45</td>
<td>108.31</td>
</tr>
<tr>
<td>4</td>
<td>15.0</td>
<td>651.94</td>
<td>90%</td>
<td>14.78</td>
<td>111.94</td>
<td>12.95</td>
<td>11.3</td>
<td>11.0</td>
<td>10.5</td>
<td>9.5</td>
<td>7.3</td>
<td>3.0</td>
<td>63.25</td>
<td>36.45</td>
<td>108.31</td>
</tr>
<tr>
<td>6</td>
<td>30.3</td>
<td>290.54</td>
<td>90%</td>
<td>12.50</td>
<td>111.91</td>
<td>11.94</td>
<td>11.6</td>
<td>10.0</td>
<td>9.2</td>
<td>7.3</td>
<td>6.0</td>
<td>5.4</td>
<td>6.11</td>
<td>4.93</td>
<td>56.08</td>
</tr>
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</table>

**DIMENSIONS OF THE SLOT:** x 3/4"

**SLOT TYPE:** P

**DIP TUBE:** 1"

**NUMBER OF SLOTS:** 8

**SUPERFICIAL GAS VELOCITY:** 8"

**S=8"**

**S=4"**

**DISCONTINUOUS Casing:**

**FLUID VELOCITY:**

**Diameter in Inches:**

**Superior Diameter:**

**Minimum Diameter:**

**SUPERFICIAL GAS VELOCITY IN Casing:**

**SUPERFICIAL LIQUID VELOCITY:**

**Comments**

**FL-3820C**

**FL-3820ST**

**FL-50000**

**MSCF**

238
Figure 5-92 shows pictures of the flow into the dip-tube for Patterson 4 and Patterson 7 when the fluid is entering in front the anchor ports and the casing pressure is 10 psi.

These pictures are shown side by side to visually compare the tests under the same conditions for each separator; included in the title of each picture is the Patterson model, the test number, the liquid velocity (VL) and the gas velocity (VG).

**Figure 5-92: Patterson 7 vs. Patterson 4 tests (Fluid entering in front the anchor ports at Pc =10 psi)**

- **Patterson 7 Test 1**
  
  (VL= 14.72 inch/sec, VG= 54.45 inch/sec)

- **Patterson 4 Test 1**
  
  (VL= 15.06 inch/sec, VG= 55.47 inch/sec)

- **Patterson 7 Test 2**
  
  (VL= 14.82 inch/sec, VG= 37.47 inch/sec)

- **Patterson 4 Test 2**
  
  (VL= 15.39 inch/sec, VG= 38.53 inch/sec)
Figure 5-92 continued

Patterson 7 Test 3  
(VL= 14.90 inch/sec, VG= 19.37 inch/sec)  

Patterson 4 Test 3  
(VL= 15.31 inch/sec, VG= 19.88 inch/sec)

Patterson 7 Test 4  
(VL= 12.12 inch/sec, VG= 55.64 inch/sec)  

Patterson 4 Test 4  
(VL= 12.39 inch/sec, VG= 55.67 inch/sec)

Patterson 7 Test 6  
(VL= 6.11 inch/sec, VG= 56.08 inch/sec)  

Patterson 4 Test 5  
(VL= 6.04 inch/sec, VG= 55.09 inch/sec)
5.5.1.2 Analysis of Patterson Models when the Fluid is entering in Front the Anchor ports

Figure 5-92, shows that the gas flow into the separator is almost the same for the same conditions for Patterson 7 and Patterson 4. Figure 5-93 shows that, under the same conditions, Patterson 4 and Patterson 7 have the same behavior.

From these tests, it is concluded that the top anchor ports do not affect the performance of this type of separator since the majority of the fluid flows into the separator through the bottom anchor ports.

It is noticed in Figure 5-93, when the liquid velocity is 12.12 inches/second and the gas velocity is 55.64 inches/second for Patterson 7, the gas rate in separator is 0.010 MSCFD and when the liquid velocity is 12.39 inches/second and the gas velocity is 55.67 inches/second for Patterson 4, the gas rate in separator is 0.00 MSCFD. This is an error in the measurements, because it is observed visually in Figure 5-92 (Test 4 for Patterson 4 and 7) that there is not difference in the gas rate going through the separator for both separators models.

Fluid Entering Below the Anchor Ports

Tables 5-15 and 5-29 show the data obtained from the tests, the data calculated for Patterson 4 and 7, respectively, when the fluid is entering in front the anchor ports, and the casing pressure is 10 psi.
Figure 5-93

PAT 4 VS PAT 7: FLUID ENTERING FRONT THE SLOTS @ 10 psi

Superficial Liquid Velocity inside Separator (in/sec)

Superficial Gas Velocity in casing annulus (in/sec)

Gas Rate through Separator (MSCF)

Patterson 4
Patterson 7
<table>
<thead>
<tr>
<th>Test No.</th>
<th>Floco Meter</th>
<th>Liquid Rate</th>
<th>Gas meter reading</th>
<th>Gas Rate</th>
<th>Gas Rate</th>
<th>Annu. Pressure</th>
<th>Port Pressure</th>
<th>Tubing Pressure</th>
<th>Superficial Liquid Velocity</th>
<th>Superficial Gas Velocity</th>
<th>Gas Rate</th>
<th>Gas Rate</th>
<th>Gas Rate</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>inches/sec</td>
<td>inches/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(sec/0.1Bbl)</td>
<td>%</td>
<td>D (psi)</td>
<td>D (psi)</td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
<td>psi</td>
<td>WATERFALL</td>
</tr>
<tr>
<td>1</td>
<td>19.2</td>
<td>60%</td>
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<td>75.86</td>
<td>10.5</td>
<td>10.2</td>
<td>12.3</td>
<td>10.6</td>
<td>9.5</td>
<td>298.22</td>
<td>3.04</td>
<td>7195</td>
<td>1.10</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>21.2</td>
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<td>75.86</td>
<td>10.5</td>
<td>10.2</td>
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<td>10.6</td>
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<td>7195</td>
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<tr>
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<td>75.86</td>
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<td>10.2</td>
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<tr>
<td>8</td>
<td>25.6</td>
<td>60%</td>
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<td>75.86</td>
<td>10.5</td>
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<td>3.04</td>
<td>7195</td>
<td>1.10</td>
<td>WATERFALL</td>
</tr>
</tbody>
</table>

DIMENSIONS OF THE SLOTS = 8" x 3/4"

FLUID ENTERING BELOW THE ANCHOR PORTS
Figure 5-94 shows the pictures of the tests for Patterson 4 and Patterson 7 when the fluid is entering below the anchor ports and the casing pressure is 10 psi.

**Figure 5-94:** Patterson 7 vs. Patterson 4 tests (Fluid entering below the anchor ports at $P_c = 10$ psi)

- **Patterson 7 Test 1**
  - $V_L = 9.51$ inch/sec, $V_G = 52.68$ inch/sec

- **Patterson 7 Test 2**
  - $V_L = 9.81$ inch/sec, $V_G = 38.64$ inch/sec

- **Patterson 4 Test 1**
  - $V_L = 9.13$ inch/sec, $V_G = 51.36$ inch/sec

- **Patterson 4 Test 2**
  - $V_L = 9.51$ inch/sec, $V_G = 37.14$ inch/sec
Figure 5-94 continued

Patterson 7 Test 3
(VL = 11.35 inch/se, VG = 19.86 inch/sec)

Patterson 4 Test 3
(VL = 11.51 inch/se, VG = 19.73 inch/sec)

Patterson 7 Test 4
(VL = 12.46 inch/se, VG = 6.85 inch/sec)

Patterson 4 Test 4
(VL = 12.45 inch/se, VG = 6.95 inch/sec)

Patterson 7 Test 5
(VL = 6.01 inch/se, VG = 55.69 inch/sec)

Patterson 4 Test 5
(VL = 6.06 inch/se, VG = 56.89 inch/sec)
Figure 5-94 continued

Patterson 7 Test 6  
(VL= 6.12 inch/see, VG= 38.35 inch/sec)  
Patterson 4 Test 6  
(VL= 6.09 inch/see, VG= 37.36 inch/sec)

Patterson 7 Test 7  
(VL= 6.16 inch/see, VG= 19.31 inch/sec)  
Patterson 4 Test 7  
(VL= 6.20 inch/see, VG= 20.46 inch/sec)

Patterson 7 Test 8  
(VL= 2.55 inch/see, VG= 55.47 inch/sec)  
Patterson 4 Test 8  
(VL= 2.51 inch/see, VG= 54.33 inch/sec)
5.5.1.3 Analysis of Patterson Models when the Fluid is entering Below the Anchor ports

In Figure 5-94, it is easy to observe that the gas rate in separator is almost the same under the same conditions for Patterson 7 and Patterson 4. Figure 5-95 shows that under the same conditions, Patterson 4 and Patterson 7 exhibit the same behavior.

From these tests, it is concluded that the top anchor ports are not necessary, because all the fluid goes through the bottom anchor ports.

5.5.1.4 Analysis of the Performance between Patterson 4 and Patterson 7 Models

The behavior of Patterson 4 and Patterson 7 when the fluid is injected in front or below the anchor ports is the same. Therefore, it is conclude that the top anchor ports are not necessary for the Patterson models.
Figure 5-95

PAT 4 VS PAT 7: FLUID ENTERING BELOW THE SLOTS @ 10 psi

![Graph showing fluid flow characteristics]
5.5.1.5 Performance of the Echometer Models with One Row of Anchor Ports

Echometer 3 (2” x 4” & dip tube = 1”) was chosen to be used for the discussion of the flow path. Echometer 3 has the same geometry as Echometer 1 (2” x 4” & dip tube = 1”), but with the top anchor ports partially closed.

Figure 5-96 (5-96a and 5-96b) shows the Echometer 1 and Echometer 3 models. It is observed in the pictures that Echometer 1 has four open anchor ports. Each anchor port is 2 inches long and 4 inches wide. The dip tube is 1 inch OD and 3/4 inches ID. The characteristics of the geometry of this separator are detailed in Figure 5-97.

**Figure 5-96: Echometer 1 and Echometer 3**

**Figure 5-96a: Echometer 1**

**Figure 5-96b: Echometer 3**

Upper anchor ports 75% closed with clear tape

**Fluid Entering in Front of the Ports**

Tables 5-4 and 5-30 show the data obtained from the test and the data calculated for Echometer 1 and 3, respectively, when the fluid is entering in front the anchor ports and the casing pressure is 10 psi.
### GAS ANCHOR

<table>
<thead>
<tr>
<th>ID</th>
<th>2.750 inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD Area</td>
<td>7.069 inch²</td>
</tr>
<tr>
<td></td>
<td>0.049 ft²</td>
</tr>
<tr>
<td>ID Area</td>
<td>5.940 inch²</td>
</tr>
<tr>
<td></td>
<td>0.041 ft²</td>
</tr>
</tbody>
</table>

### TOP SLOTS

| Number of Slots | 2.000 |
| Longitude       | 3.000 inches |
| Width           | 2.000 inches |
| Area of each slot | 6.000 inch²  |
| Total Area      | 12.000 inch² |
|                 | 0.042 ft²    |

### BOTTOM SLOTS

| Number of Slots | 2.000 |
| Longitude       | 4.000 inches |
| Width           | 2.000 inches |
| Area of each slot | 8.000 inch²  |
| Total Area      | 16.000 inch² |
|                 | 0.056 ft²    |

### TOTAL SLOTS AREA

| 28.000 inch² |

### DIP TUBE INSIDE THE ANCHOR

<table>
<thead>
<tr>
<th>OD</th>
<th>1.000 inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>0.750 inches</td>
</tr>
<tr>
<td>OD Area</td>
<td>0.785 inch²</td>
</tr>
<tr>
<td></td>
<td>0.005 ft²</td>
</tr>
<tr>
<td>ID Area</td>
<td>0.442 inch²</td>
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<tr>
<td></td>
<td>0.003 ft²</td>
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</tbody>
</table>

### CASING

<table>
<thead>
<tr>
<th>ID</th>
<th>6.000 inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID Area</td>
<td>28.274 inch²</td>
</tr>
<tr>
<td></td>
<td>0.196 ft²</td>
</tr>
</tbody>
</table>

### ANNULAR AREA

| Anchor/Dip Tube | 5.154 inch² |
|                | 0.036 ft²   |
| Casing-Anchor  | 21.206 inch² |
|                | 0.147 ft²   |

**Figure 5-97: Geometry of Echometer 3**
Table 5-30

SEPARATOR TYPE: Echometer 3
OD DIP TUBE=1"
NUMBER OF SLOTS = 2
DIMENSIONS OF THE SLOTS= 2" x 4"
FLUID ENTERING IN FRONT THE ANCHOR PORTS

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Floco N°</th>
<th>Liquid Rate</th>
<th>Gas Rate MCF</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Gas Rate through Separator</th>
<th>Comments</th>
</tr>
</thead>
</table>
|          | (sec/0.1BBl) | % | D | psia | D | (psl) | psia | (psl) | FL-392C SCFM | FL-392SCF
| 1        | 20.7     | 417.95     | 90% | 14.78 | 109.18 | 12.0 | 11.0 | 9.0 | 8.0 | 4.0 | 4.0 | 9.10 | 2.21 | 52.92 | 0.76 | 1.094 WATERFALL |
| 2        | 16.4     | 470.65     | 90% | 9.88 | 113.59 | 12.0 | 10.8 | 9.5 | 8.4 | 3.8 | 3.8 | 10.28 | 2.51 | 36.48 | 0.73 | 1.051 WATERFALL |
| 3        | 17.4     | 467.95     | 80% | 4.93 | 117.48 | 9.9 | 9.4 | 7.5 | 7.0 | 3.5 | 3.5 | 10.6 | 2.56 | 20.24 | 132 0.790 |
| 4        | 17.1     | 325.25     | 70% | 1.64 | 119.90 | 7.9 | 6.4 | 5.7 | 6.0 | 5.3 | 5.3 | 11.07 | 2.61 | 8.01 | 96 | 0.552 |
| 5        | 22.6     | 284.49     | 60% | 14.78 | 109.73 | 7.0 | 6.4 | 5.7 | 5.0 | 5.4 | 5.4 | 13.48 | 2.56 | 5.53 | 40 | 0.239 |
| 6        | 31.1     | 277.95     | 50% | 9.99 | 110.30 | 5.0 | 4.8 | 4.2 | 4.4 | 5.6 | 5.6 | 6.96 | 1.47 | 36.54 | 35 | 0.269 |
| 7        | 31.1     | 277.95     | 40% | 4.93 | 117.56 | 3.0 | 2.8 | 2.3 | 2.5 | 5.3 | 5.3 | 6.96 | 1.47 | 19.44 | 27 | 0.162 |
| 8        | 31.2     | 277.28     | 30% | 1.64 | 120.58 | 1.0 | 0.8 | 0.6 | 0.8 | 6.0 | 6.0 | 6.84 | 1.47 | 8.01 | 30 | 0.120 |
| 9        | 75.0     | 108.03     | 20% | 14.78 | 113.48 | 0.0 | 0.0 | 0.0 | 0.0 | 6.0 | 6.0 | 2.37 | 0.80 | 57.72 | 0 | 0.000 |

OD DIP TUBE=1"
NUMBER OF SLOTS = 2
DIMENSIONS OF THE SLOTS= 2" x 4"
Figure 5-98 shows the pictures of the tests for Echometer 1 and Echometer 3 when the fluid is entering in front the anchor ports and the casing pressure is 10 psi.

**Figure 5-98: Echometer 1 vs. Echometer 3 tests (Fluid entering in front the anchor ports at Pc =10 psi)**

- **Test 1 Echometer 1**
  (VL= 10.77 inch/sec, VG= 57.17 inch/sec)

- **Test 1 Echometer 3**
  (VL= 9.10 inch/sec, VG= 52.92 inch/sec)

- **Test 2 Echometer 1**
  (VL= 10.76 inch/sec, VG= 38.46 inch/sec)

- **Test 2 Echometer 3**
  (VL= 10.26 inch/sec, VG= 36.86 inch/sec)
Figure 5-98 continued

Test 3 Echometer 1
(VL= 10.93 inch/se, VG= 19.69 inch/sec)

Test 3 Echometer 3
(VL= 10.64 inch/se, VG= 20.24 inch/sec)

Test 4 Echometer 1
(VL= 11.04 inch/se, VG= 7.02 inch/sec)

Test 4 Echometer 3
(VL= 11.01 inch/se, VG= 6.84 inch/sec)

Test 5 Echometer 1
(VL= 6.25 inch/se, VG= 54.82 inch/sec)

Test 5 Echometer 3
(VL= 6.20 inch/se, VG= 53.86 inch/sec)
Figure 5-98 continued

Test 6 Echometer 1
(VL = 6.31 inch/sec, VG = 38.59 inch/sec)

Test 6 Echometer 3
(VL = 6.06 inch/sec, VG = 36.39 inch/sec)

Test 7 Echometer 1
(VL = 6.28 inch/sec, VG = 20.13 inch/sec)

Test 7 Echometer 3
(VL = 6.05 inch/sec, VG = 19.64 inch/sec)

Test 8 Echometer 1
(VL = 2.33 inch/sec, VG = 58.19 inch/sec)

Test 9 Echometer 3
(VL = 2.37 inch/sec, VG = 57.11 inch/sec)
5.5.1.6 Analysis of Echometer Models when the Fluid is entering in Front the Anchor Ports

Increasing the liquid velocity and/or increasing the gas velocity for Echometer 1 and Echometer 3 will increase the gas rate flowing through the separator.

Echometer models have a different response than Patterson models. Testing under the same conditions Echometer 1 and Echometer 3, a difference in behavior is shown.

Figure 5-99 shows that when the liquid velocity is between 9.10 and 11.04 inches/second, the gas rate in separator increases from 0.168 MSCFD to 0.897 MSCFD for Echometer 1 and the gas rate in separator increases from 0.592 MSCFD to 1.094 MSCFD for Echometer 3.

In Figure 5-98, a difference is observed in the gas rate going through the separator for Echometer 1 and Echometer 3 under the same conditions. It is noticed that under the same conditions, Echometer 3 produces more gas than Echometer 1, in some cases more than two times the amount.

When the liquid velocity is 10.77 inches/second and gas velocity is 57.17 inches/second for Echometer 1, and when the liquid velocity is 9.10 inches/second and gas velocity is 52.92 inches/second, and when the liquid velocity is 10.26 inches/second and gas velocity is 36.86 inches/second for Echometer 3, the “waterfall” phenomenon was observed (Figure 5-98, Test 1 Echometer 1, Test 1 Echometer 3 and Test 2 Echometer 3).

Figure 5-99 shows that when the liquid velocity is between 6.25 to 6.31 inches/second, the gas rate in separator is almost zero for Echometer 1 (Figure 5-98, Test 5 Echometer 1, Test 6 Echometer 1 and Test 7 Echometer 1) and the gas rate in separator increases from 0.120 MSCFD to 0.239 MSCFD for Echometer 3 (Figure 5-98, Test 5 Echometer 3, Test 6 Echometer 3 and Test 7 Echometer 3).

When the liquid velocity is between 2.33 and 2.37 inches/second and the gas velocity are between 57.11 and 58.19 inches/second, the gas rate in separator is zero for both separators (Figure 5-98, Test 8 Echometer 1, Test 9 Echometer 3).
From these tests, it is concluded that closing the top anchor ports for the Echometer models when the fluid is entering in front the anchor ports will increase the gas rate in separator.

**Fluid Entering Below the Ports**

Tables 5-5 and 5-31 show the data obtained from the test and the data calculated for Echometer 1 and Echometer 3, respectively, when the fluid is entering in front the anchor ports and the casing pressure is 10 psi.
Figure 5-99

ECHO 1 VS ECHO 3: FLUID ENTERING IN FRONT THE SLOTS @ 10 psi
Table 5-31

<table>
<thead>
<tr>
<th>Date</th>
<th>9/1/2004</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SEPARATOR TYPE: Echometer 3**

**OD DIP TUBE= 1"**

**NUMBER OF SLOTS = 2**

**DIMENSIONS OF THE SLOTS= 2" x 4"**

**FLUID ENTERING BELOW THE ANCHOR PORTS**

| Test N° | Flasc Meter | Liquid Rate | Gas Rate Reading | Gas Rate SCFM | Gas Rate Reading | Gas Rate SCFM | Gas Rate Reading | Gas Rate SCFM | Gas Rate Reading | Gas Rate SCFM | Gas Rate Reading | Gas Rate SCFM | Gas Rate Reading | Gas Rate SCFM | Gas Rate Reading | Gas Rate SCFM | Gas Rate Reading | Gas Rate SCFM | Gas Rate Reading | Gas Rate SCFM | Gas Rate Reading | Gas Rate SCFM |
|---------|-------------|-------------|------------------|---------------|----------------|---------------|----------------|---------------|----------------|---------------|----------------|---------------|----------------|---------------|----------------|---------------|----------------|---------------|----------------|---------------|----------------|---------------|----------------|
|         |             |             |                  |               |                |                |                |               |                |               |                |                |                |                |                |                |                |                |                |                |                |                |                |                |
| 1       | FL-3820C    | 11 6.0      | 541.20           | 90%           | 14.75          | 116.32         | 541.20         | 90%           | 14.75          | 116.32         | 541.20         | 90%           | 14.75          | 116.32         | 541.20         | 90%           | 14.75          | 116.32         | 541.20         | 90%           | 14.75          | 116.32         | 541.20         | 90%           | 14.75          |
| 2       | FL-3839ST   | 21 6.1      | 537.65           | 60%           | 9.86           | 114.93         | 537.65         | 60%           | 9.86           | 114.93         | 537.65         | 60%           | 9.86           | 114.93         | 537.65         | 60%           | 9.86           | 114.93         | 537.65         | 60%           | 9.86           | 114.93         | 537.65         | 60%           | 9.86           |
| 3       | FL-50000    | 31 5.6      | 552.43           | 30%           | 4.93           | 116.96         | 552.43         | 30%           | 4.93           | 116.96         | 552.43         | 30%           | 4.93           | 116.96         | 552.43         | 30%           | 4.93           | 116.96         | 552.43         | 30%           | 4.93           | 116.96         | 552.43         | 30%           | 4.93           |
| 4       | FL-50000    | 41 5.7      | 551.72           | 10%           | 1.64           | 120.33         | 551.72         | 10%           | 1.64           | 120.33         | 551.72         | 10%           | 1.64           | 120.33         | 551.72         | 10%           | 1.64           | 120.33         | 551.72         | 10%           | 1.64           | 120.33         | 551.72         | 10%           | 1.64           |
| 5       | FL-50000    | 53 0.6      | 282.54           | 90%           | 14.78          | 99.84          | 282.54         | 90%           | 14.78          | 99.84          | 282.54         | 90%           | 14.78          | 99.84          | 282.54         | 90%           | 14.78          | 99.84          | 282.54         | 90%           | 14.78          | 99.84          | 282.54         | 90%           | 14.78          |
| 6       | FL-50000    | 63 0.1      | 287.14           | 60%           | 9.86           | 109.18         | 287.14         | 60%           | 9.86           | 109.18         | 287.14         | 60%           | 9.86           | 109.18         | 287.14         | 60%           | 9.86           | 109.18         | 287.14         | 60%           | 9.86           | 109.18         | 287.14         | 60%           | 9.86           |
| 7       | FL-50000    | 73 0.5      | 283.19           | 30%           | 4.93           | 116.70         | 283.19         | 30%           | 4.93           | 116.70         | 283.19         | 30%           | 4.93           | 116.70         | 283.19         | 30%           | 4.93           | 116.70         | 283.19         | 30%           | 4.93           | 116.70         | 283.19         | 30%           | 4.93           |
| 8       | FL-50000    | 83 0.5      | 283.37           | 10%           | 1.64           | 116.70         | 283.37         | 10%           | 1.64           | 116.70         | 283.37         | 10%           | 1.64           | 116.70         | 283.37         | 10%           | 1.64           | 116.70         | 283.37         | 10%           | 1.64           | 116.70         | 283.37         | 10%           | 1.64           |
| 9       | FL-50000    | 93 3.0      | 104.10           | 90%           | 14.78          | 102.19         | 104.10         | 90%           | 14.78          | 102.19         | 104.10         | 90%           | 14.78          | 102.19         | 104.10         | 90%           | 14.78          | 102.19         | 104.10         | 90%           | 14.78          | 102.19         | 104.10         | 90%           | 14.78          |

- **FLUID ENTERING BELOW THE ANCHOR PORTS**
- **SEPARATOR TYPE: Echometer 3**
- **OD DIP TUBE= 1"**
- **NUMBER OF SLOTS = 2**
- **DIMENSIONS OF THE SLOTS= 2" x 4"**

**Comments:**

- WATERFALL
Figure 5-100 shows the pictures of the tests for Echometer 1 and Echometer 3 when the fluid is entering below the anchor ports and the casing pressure is 10 psi.

**Figure 5-100: Echometer 1 vs. Echometer 3 tests (Fluid entering below the anchor ports at Pc = 10 psi)**

Test 1 Echometer 1  
(VL= 11.79 inch/se, VG= 51.11 inch/sec)  
Test 1 Echometer 3  
(VL= 12.97 inch/se, VG= 51.93 inch/sec)

Test 2 Echometer 1  
(VL= 11.78 inch/se, VG= 39.22 inch/sec)  
Test 2 Echometer 3  
(VL= 13.11 inch/se, VG= 35.62 inch/sec)
Figure 5-100 continued

Test 3 Echometer 1
(VL = 12.04 inch/se, VG = 20.28 inch/sec)

Test 3 Echometer 3
(VL = 12.91 inch/se, VG = 20.44 inch/sec)

Test 4 Echometer 1
(VL = 11.94 inch/se, VG = 6.89 inch/sec)

Test 4 Echometer 3
(VL = 12.81 inch/se, VG = 6.82 inch/sec)

Test 5 Echometer 1
(VL = 5.99 inch/se, VG = 57.69 inch/sec)

Test 5 Echometer 3
(VL = 6.43 inch/se, VG = 55.68 inch/sec)
Figure 5-100 continued

Test 6 Echometer 1
(VL= 5.95 inch/sec, VG= 38.50 inch/sec)

Test 6 Echometer 3
(VL= 6.49 inch/sec, VG= 38.00 inch/sec)

Test 7 Echometer 1
(VL= 5.99 inch/sec, VG= 20.06 inch/sec)

Test 7 Echometer 3
(VL= 6.48 inch/sec, VG= 20.47 inch/sec)

Test 8 Echometer 1
(VL= 2.67 inch/sec, VG= 57.66 inch/sec)

Test 9 Echometer 3
(VL= 3.01 inch/sec, VG= 57.12 inch/sec)
5.5.1.7 Analysis of Echometer Models when the Fluid is entering Below the Anchor Ports

Increasing the liquid velocity and/or increasing the gas velocity for Echometer 1 and Echometer 3 will increase the gas rate flowing through the separator.

In Figure 5-100, it is observed that there is not too much difference visually in gas rate in separator between Echometer 1 and Echometer 3 at the same conditions.

Figure 5-101 shows that when the liquid velocity is between 11.72 and 12.04 inches/second, the gas rate in separator increases from 0.766 MSCFD to 1.094 MSCFD for Echometer 1 and the gas rate in separator increases from 0.748 MSCFD to 1.188 MSCFD for Echometer 3. On average, Echometer 3 produces 1.07 times more gas than Echometer 1.

When the liquid velocity is 11.79 inches/second and gas velocity is 51.11 inches/second for Echometer 1, and when the liquid velocity is 11.80 inches/second and gas velocity is 49.88 inches/second for Echometer 3, the “waterfall” phenomenon was observed (Figure 5-100, Test 1 Echometer 1 and Test 1 Echometer 3).

Figure 5-101 shows that when the liquid velocity is between 5.95 to 6.26 inches/second, the gas rate in separator increases from 0.269 MSCFD to 0.628 MSCFD for Echometer 1 (Figure 5-100, Test 5 Echometer 1, Test 6 Echometer 1 and Test 7 Echometer 1) and the gas rate in separator increases from 0.150 MSCFD to 0.389 MSCFD for Echometer 3 (Figure 5-100, Test 5 Echometer 3, Test 6 Echometer 3 and Test 7 Echometer 3). On average, Echometer 1 produces 1.44 times more gas than Echometer 3.

When the liquid velocity is between 2.37 and 2.96 inches/second and the gas velocity are between 52.45 and 53.64 inches/second, the gas rate in separator is zero for both separators (Figure 5-100, Test 8 Echometer 1, Test 9 Echometer 3).
Figure 5-101
ECHO 1 VS ECHO 3: FLUID ENTERING BELOW THE SLOTS @ 10 psi
5.5.1.8 Analysis of the Performance between Echometer 1 and Echometer 3 Models

From these tests, it is concluded that when the fluid is injected in front of the anchor ports, Echometer 3 has almost 3.5 times more gas going through the separator than Echometer 1.

When the fluid is injected below the anchor ports, at liquid velocities between 11.72 and 12.04, Echometer 3 has 1.07 times more gas going through the separator than Echometer 1 and at liquid velocities between 5.95 and 6.26, Echometer 1 has 1.07 times more gas going through the separator than Echometer 3.

Because the differences in gas rate in separator are very small in Figure 5-101, it is noticed that Echometer 1 and Echometer 3 have almost the same behavior when the fluid is entering below the anchor ports. This is a typical behavior of all the separators tested in this study. In section 5.2 (Effect of Anchor Port Width on Separator Efficiency), when a comparison is made of the Patterson models, and the fluid is entering below the anchor ports, it is shown all the separators have a similar behavior. Therefore, it is concluded that there is almost no difference between Echometer 3 and Echometer 1 when the fluid is entering below the anchor ports.

To analyze when the fluid is entering in front the anchor ports is very difficult because in order to duplicate the same conditions, it is necessary to not only have the same casing pressure, liquid velocity and gas velocity, it is also necessary to duplicate the exact position of the anchor ports facing the perforations in the casing. To duplicate the exact position of the anchor ports with respect to the perforations is hard to accomplish in the lab, but, in the field, it is impossible.

In the real world, the most popular scenario is when the fluid is entering below the anchor ports. Therefore, for this case the top anchor ports are not necessary. It is concluded that for the Patterson Models and the Echometer model, the top anchor ports are not necessary. For this reason, the Bucket model was constructed.
5.5.2 Flow Patterns in the Separator Casing and Dip Tube

5.5.2.1 Flow Pattern inside the Anchor

Plotting the superficial liquid velocities vs the superficial gas velocities in the separator on the Taitel-Ducker flow regime map (Figure 2-3), it is noticed that the flow patterns in the separator are bubble and slug or churn (Figure 5-102 area inside the red rectangle). Visually these flow patterns were observed in the tests.

5.5.2.2 Flow Pattern inside the Casing

Plotting the superficial liquid velocities vs the superficial gas velocities in the casing on the Taitel-Ducker flow regime map (Figure 2-3), it is noticed that the flow pattern in the casing are slug or churn and bubble (Figure 5-103 area inside the red rectangle). Visually these flow patterns were observed in the tests.

5.5.2.3 Flow Pattern inside the Dip Tube

Plotting the superficial liquid velocities vs the superficial gas velocities inside the dip tube on the Taitel-Ducker flow regime map (Figure 2-3), it is noticed that the flow pattern in the dip tube are bubble and slug or churn (Figure 5-104 area inside the red rectangle). Visually, the most common flow pattern observed in the tests was bubble.
Figure 5-102 Flow pattern inside the anchor

<table>
<thead>
<tr>
<th>s</th>
<th>Superficial Gas Velocity in Separator</th>
<th>Superficial Gas Velocity in Separator</th>
</tr>
</thead>
<tbody>
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<tr>
<td>3</td>
<td>0.30 inches/sec</td>
<td>6.94 m/s</td>
</tr>
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<td>3</td>
<td>0.30 inches/sec</td>
<td>6.17 m/s</td>
</tr>
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<td>0.30 inches/sec</td>
<td>4.63 m/s</td>
</tr>
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<td>3</td>
<td>0.30 inches/sec</td>
<td>3.47 m/s</td>
</tr>
<tr>
<td>1</td>
<td>0.29 inches/sec</td>
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<td>7</td>
<td>0.32 inches/sec</td>
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<td>9</td>
<td>0.15 inches/sec</td>
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<td>3</td>
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<td>6</td>
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<td>0.10 m/s</td>
</tr>
<tr>
<td>0</td>
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</table>
Figure 5-103 Flow pattern in the casing

Table: TYPICAL SUPERFICIAL VELOCITIES IN THE TESTS

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<tr>
<th>Superficial Liquid Velocity in Separator</th>
<th>Superficial Liquid Velocity in Separator</th>
<th>Superficial Gas Velocity in Separator</th>
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</tr>
</thead>
<tbody>
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<td>inches/sec</td>
<td>m/s</td>
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<tr>
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<tr>
<td>1.47</td>
<td>0.04</td>
<td>20.03</td>
<td>0.51</td>
</tr>
<tr>
<td>0.75</td>
<td>0.02</td>
<td>55.68</td>
<td>1.41</td>
</tr>
</tbody>
</table>
Figure 5-104 Flow pattern in the dip tube

<table>
<thead>
<tr>
<th>Superficial Liquid Velocity in Dip Tube (Inches/sec)</th>
<th>Superficial Liquid Velocity in Dip Tube (m/s)</th>
<th>Superficial Gas Velocity in Dip Tube (Inches/sec)</th>
<th>Superficial Gas Velocity in Dip Tube (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>143.10</td>
<td>3.63</td>
<td>85.60</td>
<td>2.17</td>
</tr>
<tr>
<td>141.08</td>
<td>3.58</td>
<td>83.33</td>
<td>2.12</td>
</tr>
<tr>
<td>141.08</td>
<td>3.58</td>
<td>74.07</td>
<td>1.88</td>
</tr>
<tr>
<td>141.08</td>
<td>3.58</td>
<td>55.56</td>
<td>1.41</td>
</tr>
<tr>
<td>141.08</td>
<td>3.58</td>
<td>41.67</td>
<td>1.06</td>
</tr>
<tr>
<td>138.39</td>
<td>3.51</td>
<td>39.35</td>
<td>1.00</td>
</tr>
<tr>
<td>141.08</td>
<td>3.58</td>
<td>36.00</td>
<td>0.91</td>
</tr>
<tr>
<td>148.04</td>
<td>3.78</td>
<td>24.93</td>
<td>0.83</td>
</tr>
<tr>
<td>71.44</td>
<td>1.81</td>
<td>19.39</td>
<td>0.49</td>
</tr>
<tr>
<td>71.90</td>
<td>1.83</td>
<td>9.97</td>
<td>0.25</td>
</tr>
<tr>
<td>72.51</td>
<td>1.84</td>
<td>1.22</td>
<td>0.03</td>
</tr>
<tr>
<td>36.92</td>
<td>0.94</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

TYPICAL SUPERFICIAL VELOCITIES IN THE TESTS
5.5.2.4 Waterfall

When the superficial liquid velocity inside the separator is more than 9 inches/second and the superficial gas velocity in the casing is more than 39 inches/second, a phenomenon is presented that in this project is called “waterfall”. This phenomenon mostly occurs in cases in which the fluid is entering below the anchor ports and when the casing pressure is 10 psi. It is called waterfall because inside the separator, an annulus of falling water is formed and inside this ring, there is gas rising. Figure 5-105 (5-105a and 5-105b) show this phenomenon.

Plotting the superficial liquid velocities vs the superficial gas velocities inside the separator on the Taitel-Ducker flow regime map (Figure 2-3), when this phenomenon is occurred, it is noticed that the flow pattern in the separator is bubble (Figure 5-106 area inside the red rectangle), but visually, the flow pattern observed is annular. Therefore, besides the velocities, in this case, the flow pattern depends on other factors as pressure, position of the anchor ports, etc.

Figure 5-105: Waterfall

Figure 5-105a

Figure 5-105b
### Table 5-32 Superficial liquid and gas velocities showed in the waterfalls

<table>
<thead>
<tr>
<th>SEPARATOR MODEL</th>
<th>Superficial Liquid Velocity in Separator</th>
<th>Superficial Liquid Velocity in Casing</th>
<th>Superficial Gas Velocity in Separator</th>
<th>Superficial Gas Velocity in Casing</th>
<th>Superficial Liquid Velocity in Diphone</th>
<th>Superficial Gas Velocity in Diphone</th>
<th>Gas Rate through Separator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUCKET</td>
<td>12.10 0.31 2.38 0.06 4.17 0.11 53.10 1.35 141.08 3.58 50.00 1.27 1.080 WATERFALL</td>
<td>11.04 0.28 2.18 0.06 4.06 0.10 37.14 0.94 141.08 3.58 48.67 1.24 1.051 WATERFALL</td>
<td>13.16 0.33 2.59 0.07 6.11 0.16 51.50 1.31 141.08 3.58 73.33 1.86 1.564 INTERMITTENT WATERFALL</td>
<td>13.30 0.34 2.62 0.07 5.83 0.15 34.57 0.88 141.08 3.58 70.00 1.78 1.512 INTERMITTENT WATERFALL</td>
<td>9.72 0.25 2.36 0.06 0.58 0.01 70.03 1.78 138.39 3.51 6.92 0.18 0.150 WATERFALL</td>
<td>10.72 0.27 2.62 0.07 3.46 0.09 57.17 1.45 141.08 3.58 41.54 1.06 0.897 WATERFALL</td>
<td>ECHOMETER 1 11.79 0.30 2.87 0.07 4.22 0.11 51.11 1.30 148.64 3.78 50.67 1.29 1.094 WATERFALL</td>
<td>ECHOMETER 2 9.77 0.25 1.92 0.05 1.87 0.05 67.62 1.72 71.44 1.81 22.43 0.57 0.485 WATERFALL</td>
</tr>
</tbody>
</table>
Figure 5-106 Flow pattern in the anchor for waterfall
6. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are based on the previous discussion and the observation of the flow characteristics as illustrated in the photos and the numerous video clips recorded during this study.

6.1 Conclusions

1. The best position to place a downhole gas separator is where the slots are below the perforations. The distance between the slots and the last perforation needs only to be a few feet. In this position, very little gas will enter the downhole gas separator as long as the downwards liquid velocity in the annulus is less than 6 inches per second.

2. When the fluid is entering below the slots (the most common position in field installations), all of the separator models tested that have the same diptube diameter have almost the same behavior.

3. The volume of gas flowing through the separator, when it is located with the entry ports at or above the casing perforations, is a function of at least two variables: a) The liquid superficial velocity inside the separator and b) The gas superficial velocity in the annulus between the casing and the separator.

4. As the annular gas superficial velocity increases the liquid superficial velocity inside the separator must decrease in order to maintain a high separation efficiency.

5. Increasing the slot width will decrease the gas rate going through the separator when the fluid is entering in front the slots for the Patterson models.
6. Pressure drop in the system (between the slots and the entrance to the pump) depends directly on the dip tube internal diameter and length. A long dip tube will generate more pressure loss in the system. The tests indicate that it is not necessary to have a long dip tube to get a good gas separation.

7. A large dip tube external diameter increases the gas rate going through the separator.

8. It is not necessary to have a long downhole gas separator; the length of the separators tested of 6 feet (5.5-foot dip tube) resulted in efficient separation.

9. Annular static pressure influences performance. The lower the annular pressure, the better the performance. In this project, with a casing pressure equal to 5 psig (19.7 psia), the gas going through the separator is smaller than when the casing pressure is equal to 10 psig (24.7 psia).

10. Increasing the superficial gas velocity in casing reduces the performance of the separator.

11. It is observed that the top slots do not contribute to admitting liquid in the separator; therefore, it is not necessary to design a downhole gas separator with multiple rows of slots provided that gas exit ports are located at the top of the separator.

12. It was believed that for liquid velocities in separator less than 6 inches/second, there is good separation, but as this study has demonstrated, the design liquid velocity in separator depends on the factors that have been discussed herein, namely: position of the slots, slot width, dip tube diameter and pressure effect.

13. When the superficial liquid velocity is greater than 9 inches/second and the superficial gas velocity in casing is greater than 35 inches/second (greater than 75 MSCFD), the “waterfall” flow occurs within the separator. This phenomenon occurs almost always when the fluid is about to enter below the slots.
14. Observations indicate that gas bubbles become trapped in low pressure areas at reverse flow and do not escape, but break up and are dragged by the liquid to the dip tube.

15. Having small slots can help the gas bubbles break up into small ones which will be dragged by the liquid to the dip tube.

16. It is shown in Appendix E how it is possible to calculate the pressure in the pump (P2) and the drop pressure in the system when the pressure in the slots or the casing pressure is known.

6.2 Recommendations

1. The effect of the viscosity of the liquid is thought to be an important parameter; therefore, it is recommended to continue the current project, changing the viscosity of the fluid.

2. The behavior of these separator models that have a high gas and liquid rate is understood very clearly in this project. It is recommended to run a series of tests with low liquid and gas velocities to define more accurately the zero curve in different situations.

3. The pressure effect was studied using 5 and 10 psi. It is recommended to study the pressure effect using 15 psi to identify if there is a change.

4. To study in detail the behavior of the separator when it is located in front of the perforations, it is necessary replicate exactly the position of the slots and their alignment with the perforations. These tests should be repeated.

5. The superficial liquid velocity in the casing is an important factor; therefore, it would be good to change the separator outside diameter (to change the annulus area between the casing and the anchor).
6. The tests run for this project simulate a continuous flow (Progressive Cavity Pumps and Electro Submersible). Therefore, to understand the performance of the separator when used with Sucker Rod Pumps, it is necessary to modify the apparatus in order to control the flow intermittently to simulate the fact that in Sucker Rod Pumps there is fluid entering the separator only during the pump’s upstroke.

7. The differences in surface properties of the fluids would affect the results. If the well is treated with chemical products for any common problem as corrosion, paraffin, asphaltene, etc, the properties of the liquid and gas may change affecting the separation. Even trace amounts of surface-active chemicals can have an effect. Crude oils DO have small amounts of surface-active components.
APPENDIX A

Summaries of 42 patents of downhole gas separators

These patents are divided into two groups: Centrifugal Gas-Separators and Gravity gas separators. The Centrifugal gas separators are subdivided into the following categories: Dynamic and Static.
This summary of patents will help us in the design of the downhole separator test system.

Centrifugal Gas Separator (Static)

Gas Anchor

Patent № 3128719

This gas anchor consisting of a cylindrical housing sealed at the bottom, at least one sheet metal helix accommodated in the housing, and a tube, one side of which communicates with the space underneath the sheet metal helix. A gas discharge conduit is centrally positioned in the housing, which conduit is provided with openings, preferably near the side of the sheet metal helix facing the bottom of the housing. Preferably the top of the helical channel between the housing, the gas discharge conduit and the sheet, communicates with the outside of the housing.
Bottom-hole gas-liquid separator

**Patent No° 4074763**

This separator is a downhole apparatus useful in a well for separate gas from liquid. This separator utilizes centrifugal force to assist in separating gas from liquid and includes a central inner tubular member for flowing gas thus separated through the incoming gas-liquid mixture and also an annular passage for gas flow up through the incoming gas-liquid mixture.
Liquid-gas separator apparatus

Patent N° 4231767

This downhole liquid-gas separator is for use with a submersible pump. This apparatus employs an inverted conical, convoluted, fine-mesh screen in a tubular housing. The convolutions form grooves extending upwardly along the screen. A liquid-gas mixture enters the housing near the lower, apex end of the screen. The screen mesh size is selected so that liquid is pumped through the screen and continues to flow upwardly through the housing, while gas bubbles rise along the exterior of the screen and
are vented from the housing. The gas bubbles channel into the troughs of the screen grooves, leaving the peak regions of the convolutions free for the passage of liquid. A relief valve arrangement bypasses the screen when it becomes clogged, and permits the liquid-gas mixture to flow upwardly through the housing.

Figure A-3: Liquid-gas separator apparatus (U.S. Patent № 4,231,767)

Downhole concentric chamber gas separator and method
Patent № 5240073

This downhole separator has a first tube having a first end and a second end, the first end being adapted for connection to an end of a production tubing, an outer annular space being defined between the first tube and a casing string; a second tube, having a smaller diameter than the first tube, and being disposed within the first tube, an inner
annular space being defined between the second tube and the first tube, the second tube having an inlet end and an outlet end, the outlet end being turned at an angle relative to a longitudinal axis of the second tube and communicating with the outer annular space, the inlet end passing sealingly through the second end of the first tube to communicate with the producing formation, the first tube having perforations at a point below the outlet end of the second tube to allow communication between the outer annular space and the inner annular space.

Figure A-4: Downhole concentric chamber gas separator and method

(U.S. Patent N° 5,240,073)
Downhole gas-liquid separator for wells

Patent № 5431228

A downhole gas-liquid separator for multiphase fluid producing wells includes a tubular member with a spiral baffle disposed therein and a duct including an inlet disposed adjacent the discharge end of the spiral baffle. Fluid flow into the separator undergoes substantial gas and liquid separation by centrifugal forces imposed on the liquid as it progresses through the spiral flow path. Gas is drawn off at the discharge end of the spiral baffle and discharged into the wellbore annulus while liquid and a small amount of gas pass on through the separator and the production tubing to the surface. The spiral baffle may be disposed in the wellbore between the distal end of the production tubing string and the point of entry of gas and liquid into the wellbore. The separator may include a retrievable tubular body inserted in a ported nipple interposed in the tubing string.

Figure A-5: Downhole gas-liquid separator for wells

(U.S. Patent № 5,431,228)
Downhole gas separator
Patent № 5653286

A downhole gas separator is connected to the lower end of a tubing string. The separator includes a tubular body which has a decentralizer mounted to one side for driving the opposite side of the separator against an interior wall of the casing. This creates a narrow flow zone between the separator body and the adjacent casing wall and a wider flow zone on the decentralizer side of the body. A fluid inlet is provided on the side of the gas separator tubular body facing the narrow flow zone. The fluid in the narrow flow zone has a substantially higher concentration of liquid than the fluid in the wider flow zone. Fluid, primarily liquid, flows through the fluid inlet into a chamber within the separator. A dip tube transfers the fluid from the separator chamber to the pump.

Figure A-6: Downhole gas separator (U.S. Patent № 5653286)
Centrifugal Gas Separator (Dynamic)

Liquid-gas separator unit  
**Patent No Re30836 and Patent No 3887342**

The unit is characterized by a high liquid flow rate capacity at high as well as low accompanying gas flow rates, and efficient liquid-gas separation capability. The unit has a unique discharge plug element and a unique intake plug element that cooperate with a unique impeller means. Inlet/recirculation openings in the unit casing act to increase the liquid flow rate.

**Figure A-7: Liquid-gas separator unit (U.S. Patent No Re 30,836)**
Figure A-8: Liquid-gas separator unit (U.S. Patent No 3,887,342)
Gas Separator
Patent No. 3175501

This is a gas separator for interposing between the motor (with or without a separator seal) and the pump, the latter being located at the upper end of the submersible motor pump assembly. This separator is provided with an outer housing with inlet ports therein and an inner sleeve or crossover tube, both of which are coaxial with the interconnecting motor with the pump unit. The outlet housing is closed at the bottom to form a reservoir for a supply of fluid to an impeller. The impeller has an inlet which opens upwardly so that any gas tending to form at the inlet to the impeller may bubble back through the fluid in the reservoir. In the event of a gas surge, the upturned inlet
prevents a continuous gas-lock or bubble, which would normally from under these circumstances to prevent fluid from entering the pump by operation of gravity when fluid, is again available.

The fluid which flows in a direction upwardly past the outside of the housing will flow downwardly on the inside of the housing. This reversal of flow separates some of the gas from the liquid. As the fluid enters the upturned inlet and is forced upwardly by the separator impeller, the fluid again reverses flow so that this again reduces gas entering the pump inlet.

**Figure A-9: Gas separator (U.S. Patent № 3,175,501)**
Sand and Gas Separator

Patent № 3285186

This apparatus includes a means for inducing a spin to the sand and gas laden water so as to separate both the sand and the gas from the water before it enters the inlet of the pump and to provide means for efficient removal of the sand and gas from the separator so as to maintain the separator operation at a high efficiency level.

Figure A-10: Sand and gas separator (U.S. Patent № 3,285,186)
Gas Separator for Submersible Pump

Patent N° 3291057

This unit is adapted to be positioned between motor and pump in surrounding relation to an interconnecting drive shaft which is operable by the motor. This separator includes an elongated housing extending downwardly from the pump unit which is divided into an outer annular chamber adjacent the housing and an inner annular chamber adjacent the drive shaft by an inner sleeve or flow tube extending downwardly from the pump inlet. The fluids enters the reservoir chamber through the openings in the top of the housing and passes downwardly through the reservoir chamber and cross-over housing into the upwardly directed gas separator pump impeller inlet adjacent the drive shaft. The fluid is pumped radially outwardly and returned by way of the cross-over housing to the inner annular chamber defined by the flow tube and drive shaft. Gas is separated as it enters the opening in the separator housing.

Figure A-11: Gas separator for submersible pump (U.S. Patent N° 3,291,057)
Centrifugal Gas Separator

Patent N° 3300950

This centrifugal gas separator is relatively short in length and therefore relatively inexpensive to manufacture as compared with to others gas separators. This separator comprises an impeller which will subject fluid entering the separator to centrifugal force and cause the gas and liquid to separate before entering the submersible pump inlet.

Figure A-12: Centrifugal gas separator (U.S. Patent N° 3,300,950)
Gas Separator for a Submersible oil Pump

Patent № 3624822

This unit is a gas separator interposed between a submersible pump and electric motor includes a plurality of flow diversion means including a coaxial impeller for impelling well fluid through a spiral gas separator chamber from the well fluid. The gas passes into and through a gas-collecting receptacle and subsequently is returned back into the well fluid basin while the well fluid progresses from the gas separator chamber into the inlet of the pump. The inlet to the impeller includes a plurality of vertically nested inlet cylinders or cups through which the flow of fluids is controlled.

Figure A-13: Gas separator for submersible oil pump (U.S. Patent № 3,624,822)
Discharge element for a liquid-gas separator unit

Patent № 3972352

The present invention comprises a discharge element for use at the upper end of a liquid-gas separation chamber wherein gas is separated from a liquid-gas mixture prior to discharge of the liquid component of the mixture through the discharge element. A discharge element may comprise an annular body having an axial wall and at least one passageway terminating at its upper end in an aperture through said wall to provide communication between the outside and inside of said annular body for conveying liquid through the wall of the discharge element, said passageway including an outside wall segment leading upwardly from the lowermost end of said body and curving in substantially helical fashion around a vertical axis through said body toward said aperture.

Figure A-14: Discharge element for a liquid-gas separator unit

(U.S. Patent № 3,972,352)
Device for separating multiple phase fluid systems according to the relative specific gravities of the phase

Patent N° 4072481

This apparatus is a device for separating multiple phase fluid systems according to the relative specific gravities of the phase.

This separate has a vortex chamber providing upper and lower ends and a circumscribing side wall, a supply conduit connected to the upper end of the chamber adapted to supply a fluid system to the chamber so as to cause it to swirl in the chamber to throw a heavier phase outwardly to descend in the chamber and to cause a lighter phase to move inwardly in the chamber, a tubular vortex finder extended in the upper end of the chamber about which said system is swirled having an open end in downwardly spaced relation to the upper end of the chamber through which a phase of intermediate specific gravity is discharged, a conduit connected to the lower end of the chamber to remove the heavier phase from that, a partition in the upper end of the chamber extended between the vortex finder and the wall of the chamber to define a collecting compartment there above, said partition having an opening through that adjacent to the vortex finder for the passage of the lighter phase therethrough into the compartment, and a conduit connected to the compartment to draw the lighter phase therefrom.
Figure A-15: Device for separating multiple phase fluid systems according to the relative specific gravities of the phase (U.S. Patent N° 4,072,481)
Anti-gas locking apparatus

Patent № 4386653

An anti-gas locking apparatus for a downhole pump comprises a sleeve disposed below the pump and in fluid communication with the pump inlet, a housing disposed about the sleeve and fluidly communicating at its upper end with the well in which the pump is disposed, and a cross-over assembly communicating lower portions of the housing with the lower end of the sleeve. The cross-over assembly comprises a cross-over diffuser including a jacket member, the upper end of which mates with the lower end of the sleeve, and a dome member within the jacket member.

Apertures are formed through the jacket member and dome member and webs extend between these members to form inlet passages into the interior of the dome member from the annulus between the housing and the sleeve and outlet passages about the dome member to the sleeve. An impeller is disposed within the jacket member below the dome member.

Disclosed is an improved geometry of the cross-over diffuser in which webs forming the walls of the inlet and outlet passage spiral about the dome member with ever increasing vertical slope to a substantially vertical disposition and the diffuser is provided with similarly shaped flow shaping vanes within the outlet passages. The impeller is provided with vanes that increase in vertical dimension from the center of the impeller toward the periphery thereof so that, with the improved geometry of the diffuser, turbulence of well fluids passing through the diffuser is avoided.
Liquid-gas separator apparatus

Patent N° 4481020

This is a centrifugal liquid-gas separator apparatus which is particularly adapted for use downhole with a submersible pump comprises an elongated hub having disposed on its periphery helical blades defining a screw-type inducer for pressurizing a liquid-gas fluid mixture entering the apparatus, axially extending vanes defining a centrifugal separator for separating the liquid and gas components of the fluid mixture, and smoothly
curved blade segments disposed intermediate the blades and the vanes for providing a smooth transition for the fluid mixture flowing from the inducer to the centrifugal separator. The apparatus is capable of maintaining a substantially constant flow rate over a large range of volumetric ratios of gas to liquid.

Figure A-17: Liquid-gas separator apparatus (U.S. Patent N° 4,481,020)
Downhole oil/gas separator and method of separating oil and gas downhole
Patent № 4531584

The oil/gas separator of this invention includes a separation chamber having a continuously upwardly spiralling ramp and an internal collection tube to collect the separated gas and move the gas upwardly and out of the tool and into the annulus of the oil well. The method of this invention is practiced by directing an oil/gas mixture from a producing zone in a helical direction to impart centrifugal separating velocity at varying levels to the mixture to cause gas to separate from the mixture.

Figure A-18: Downhole oil/gas separator and method of separating oil and gas downhole (U.S. Patent № 4,531,584)
Method and apparatus for establishing multi-stage gas separation upstream of a submersible pump (Two Stages)

Patent No. 4901413

A method for constructing a multiple-stage gas separator assembly for downhole use upstream of a hydrocarbon producing submersible pump system (ESP) is disclosed which has steps for forming a first-stage gas separator from a first conventional single-stage gas separator, connecting a coupling assembly to the first-stage gas separator at its downstream end, forming a second-stage gas separator from a second conventional single-stage gas separator by removing all lower flanges upstream of its fluid inlet, connecting the upstream end of the second-stage gas separator to the coupling assembly,
and establishing a flow path from the first-stage liquid outlet to the second-stage inlet through the coupling assembly. A coupling assembly for joining first and second single-stage gas separators into a multiple-stage gas separator is also disclosed in which the coupling assembly has means for attaching to the downstream end of a first-stage gas separator, and a coupling housing defining a flow path between the liquid outlet of the first-stage gas separator and the fluid inlet of the second-stage gas separator. In an alternate embodiment, an adaptor is disclosed for inclusion into the coupling assembly which provides flow paths and a bushing for the second-stage gas separator formed from an alternate commercially available single-stage gas separator configuration.

**Figure A-20: Method and apparatus for establishing multistage gas separation upstream of a submersible pump (two stages) (U.S. Patent N° 4, 901,413)**
Method and apparatus for high-efficiency gas separation upstream of a submersible pump (Two Stages)

Patent N° 4913630

A submersible pump system (ESP) and method for producing oil from gassy wells is disclosed in which at least first and second stage gas separators protect a submersible pump from vapor lock. The pump communicates with the production tubing and is driven by a shaft extending from a motor, through the first- and second-stage gas separators. The first-stage gas separator has a first-stage inlet through the housing in communication with the production fluid from the producing formation.

A primary means for separating gas components from the production fluid is in communication with the first-stage inlet and expels separated gas into the annulus through a first-stage gas outlet and advances the liquid component of the production fluid through the first-stage liquid outlet. The second-stage gas separator has a second-stage inlet communicating with the first-stage liquid outlet and leading to a secondary means for separating the gas from the production fluid. The separated gaseous components are expelled through the housing and into the annulus at a second-stage gas outlet while the retained liquid components of the production fluid are presented to the pump, or to additional separation stages, through a second-stage outlet. The production fluid ultimately entering the pump inlet is substantially limited to the liquid components of the production fluid which is pumped through a pump outlet and up the production tubing.
Recirculating gas separator for electric submersible pumps

Patent No 4981175

A re-circulating gas separator for a submersible well pump (ESP) includes a rotary gas separator for separating liquid to be directed to the pump from a gas. The separator includes a separating chamber, a well fluid inlet upstream of the separating chamber, and a liquid discharge outlet downstream of the separating chamber. A recirculating system re-circulates a portion of the liquid discharged from the discharge outlet back to the separating chamber so that a gas-to-liquid ratio in the separator is substantially lower than a gas-to-liquid ratio of well fluid entering the well fluid inlet.
Thus, the submersible well pump with the re-circulating gas separator can successfully pump wells having substantially higher gas-to-liquid ratios than can be accomplished with prior devices.

**Figure A-22: Recirculating gas separator for electric submersible pumps**

(U.S. Patent No. 4,981,175)
**System for pumping fluids from horizontal wells**

**Patent N° 5154588**

Apparatus and method for pumping fluids from horizontal wells with a dip tube used without requiring a packer in the well.

Gas is separated from the liquid phase ahead of the pump to avoid slug flow of gas into the pump. This increases the amount of oil that can be pumped from the well by avoiding shutdowns resulting from gas-locking of the pump.

**Figure A-23: System for pumping fluids from horizontal wells**

(U.S. Patent N° 5,154,588)
**Submersible well pump gas separator**

**Patent N° 5207810**

A gas separator for a submersible centrifugal pump (ESP) for a well separates gas from liquid components of the well fluid. The gas separator has a rotatably driven rotor. The rotor has an outer cylinder, an inner hub and a longitudinal vane that extends between the inner hub and outer cylinder. Gaps are formed in the upper edge of the vanes. A discharge member, mounted above the rotor, has a depending skirt that extends into the gaps. This defines a separate inner flow path for gas to flow out of the separator into the well. The unseparated portions of the well fluid flow in a clearance between the skirt and the housing into a pump intake. Supports extend out from the discharge member for securing the discharge member in the housing.

**Figure A-24: Submersible well pump gas separator (U.S. Patent N° 5,207,810)**
Abrasion resistant gas separator

Patent N° 5516360

This apparatus is a gas separator for a submersible centrifugal pump (ESP) or well has hardened cases on the components exposed to well fluid within the interior of the gas separator. The gas separator has a cylindrical sidewall with a bore. A shaft driven by a motor of the pump extends through the bore. An inducer is located in the bore for applying pressure to the fluid. In one type, a spinning guide vane imparts swirling motion for the well fluid to separate as it flows through a straight-through bore section. In another type, a tubular barrel locates in the sidewall, defining an intake chamber. The intake port in the sidewall is located above the intake port in the barrel, causing a reverse direction flow to separate gas from the liquid.

Figure A-25: Abrasion resistant gas separator (U.S. Patent N° 5, 516,360)
Rotary gas separator (PCP)

Patent N° 5525146

This apparatus is a rotary gas separator for use with a progressive cavity pump (PCP) which includes a separation housing having an internal separation chamber with a bladed separator rotatably mounted there within for separating introduced fluid into a gas constituent and a liquid constituent. Coupling mechanisms are mounted on a first end of the bladed separator for connection to a rotor of a progressive cavity pump, and for permitting limited longitudinal movement and limited transverse movement between the bladed separator and the rotor to prevent bearing failure within the drive train of the pump.

Figure A-26: Rotary gas separator (U.S. Patent N° 5, 525,146)
**Downhole gas compressor**

**Patent N° 5605193 and Patent N° 5755288**

A gas compressor is employed downhole in a well for pressurizing formation gas. The gas compressor is driven by a downhole electrical motor. The downhole assembly also includes a pump. The pump might be located below the motor and driven by the same motor. In that event, the pump pumps liquid being produced by the formation downward to a liquid disposal formation. Also, the pump may pump the liquid to the surface, with the gas being delivered into a repressurizing zone.

*Figure A-27: Downhole gas compressor (U.S. Patent N° 5, 605,193)*
Figure A-28: Downhole gas compressor (U.S. Patent No. 5,755,288)
Downhole pumping system for recovering liquids and gas (Mixer)

Patent N° 5628616

This apparatus comprise a first centrifugal pump having internal features for mixing introduced gas into introduced liquids and a second centrifugal pump having an intake in fluid communication with a discharge of the first centrifugal pump. In one preferred embodiment the internal features for mixing comprise improved impellers having a balance hole that extends through an upper surface of the impeller body into each of a plurality of internal flow chambers, and an additional passage in at least a plurality of the flow chambers. The additional passages cause some fluid to be recirculated in a manner that causes introduced gas to be mixed into the liquids, thereby increasing the pump's gas volume recovery ability.

Figure A-29: Downhole pumping system for recovering liquids and gas

(U.S. Patent N° 5, 628,616)
Continuous flow downhole gas separator for progressive cavity pumps
Patent N° 5902378

This apparatus is a gas separator which can be attached to the suction of a downhole pump to remove gas from the liquid being pumped prior to the liquid entering the pump inlet. The separator has an elongate housing having an annular chamber with guides which direct the liquid gas mixture to flow in an annular path from the inlet to the outlet end. During this flow centrifugal forces act to displace the gas content to the central region from which it is removed via a separate central gas outlet so that liquid delivered to the pump inlet is greatly reduced in its gas content.

Figure A-30: Continuous flow downhole gas separator for progressive cavity pumps
(U.S. Patent N° 5, 902,378)
**Tapered flow gas separation system (Two Stages)**

**Patent N° 6066193**

The present invention provides a submersible pumping system which includes a tapered flow gas separation system.

The tapered flow gas separation system includes at least a first and second gas separator. The first separator is configured to receive and process a first flow rate of production liquid. The first separator is adapted to draw production liquid from a production casing and to separate a first portion of gas from the production liquid. The second separator is configured to receive and process a second flow rate of production liquid which is less than the first flow rate received by the first separator. The second separator is adapted to receive the production liquid from the first separator and to separate a second portion of gas from the production liquid.

**Figure A-31: Tapered flow gas separation system (U.S. Patent N° 6,066,193)**
**Gas separator having a low rotating mass**

**Patent N° 6113675**

This apparatus is a gas-liquid separator that has a reduced rotating mass. The gas separator includes a stationary flow inducer that creates a vortex within an outer housing. The flow inducer includes an accelerator mechanism that increases the velocity of the fluid mixture as it flows through a portion of the gas separator. The resultant liquid and gaseous phases are directed from the gas separator through separate outlets.

**Figure A-32: Gas separator having a low rotating mass (U.S. Patent N° 6,113,675)**
Downhole gas separator having multiple separation chambers

Patent N° 6155345

The gas separator includes an outer housing having a hollow interior divided into a plurality of separation chambers. A shaft and an inducer are rotatably mounted within the hollow interior. A plurality of flow-through bearings is distributed through the hollow interior to support the rotatable shaft. Also, a plurality of vortex generators are disposed in the hollow interior to generate and maintain a fluid vortex during separation.

Figure A-33: Downhole gas separator having multiple separation chambers

(U.S. Patent N° 6,155,345)
Reverse flow gas separator for progressing cavity submergible pumping systems

Patent N° 6257333

A system for separating gas from a wellbore fluid as it is produced to the surface. The system includes a progressing cavity pump (PCP), a submergible electric motor (ESP) and a fluid intake. The submergible electric motor is connected to the progressing cavity pump to drive the pump and draw wellbore fluid through the fluid intake. The fluid intake includes a hollow interior defined by a thick-walled section. Additionally, the fluid intake includes a plurality of fluid passageways extending through the thick-walled section. The passageways are oriented to create a reversal in fluid flow, and thus a release of gas, as the fluid is draw into the fluid intake.

Figure A-34: Reverse flow gas separator for progressing cavity submergible pumping systems (U.S. Patent N° 6,257,333)
Gravity Gas Separator

Gas Separators for Well Pumps
Patent № 2748719

This apparatus provides suitable means for directing the well fluid into the gas column. These means may include a fluid directing baffle, which may have a perforated screen-like portion acting to divide the fluid flow into a plurality of individual streams, each of which is very intimately contacted and surrounded by the gases of the gas column.

The pump section may be utilized to produce a force serving to withdraw fluid from one side of the baffle in a manner such that fluid flows through the baffle from its second side to the first side and into an upper gas space at that first side. The baffle may extend vertically within an inner chamber of the separator, and may have a lower imperforate portion adapted to direct the fluid upwardly through an upper perforated portion thereof.

The separate liquid may be withdraw from the device through an outlet, typically a liquid discharge outlet or pipe may communicate with the separating chamber at a location lower than the perforated portion of the baffle, and opposite its imperforate portion.
Figure A-35: Gas Separators for well pumps (U.S. Patent N° 2,748,719)
Multiple cup downwell gas separator

Patent № 4241788

This gas separator includes a plurality of upwardly opening retention cups which are disposed in vertical spaced relationship one above the other above a reservoir chamber. Each retention cup has a retention chamber which provides a fluid retaining capacity sufficient to momentarily retain well fluid flowing from the well so as to permit gas to escape from the fluid so retained and returned to the well. The difference in specific gravity between gassy fluid and fluid with gas removed increases circulation of well fluid through the retention cups and into the reservoir chamber, with each retention cup catching down falling well fluid that has been partially freed of entrained gas. Second stage separation of gas from well fluid is achieved by providing at least one opening or passageway from the reservoir chamber adapted to provide a gas exit between the well and the reservoir chamber.

Figure A-36: Multiple cup downhole gas separators (U.S. Patent № 4,241,788)
Downhole gas separator

Patent № 436861

A downhole gas separator for use with a downhole pump in a producing well bore, the gas separator being secured to the lower end of the pump and generally comprises inner and outer concentrically arranged tubes extending downwardly within the well tubing, the first tube being provided with a plurality of perforations in the sidewalls thereof adjacent the upper portion thereof, and the second tube being provided with a plurality of perforations in the sidewalls thereof adjacent the lower portion thereof.

The well fluid contained in the well bore is drawn into the well casing and travels through a long, torturous upward and downward path through the well tubing and gas separator and to the surface of the well bore, with substantially all of the gas being separated from the heavier components of the fluid during the travel.

The gas separator is preferably of an overall length at least approximately equal to the length of a single well tubing joint to provide sufficient length of travel for the well fluid to remove substantially all of the entrained gas and to filter substantially all debris from the fluid stream. This length is approximate 15 ft.
Downhole gas anchor device

Patent N° 4676308

This separator diverts hydrocarbon production fluid from within a tubing string into the annulus of the well. This diversion turbulently mixes the fluid and releases free gas from the liquid. Thereafter, the liquid migrates downward while the free gas migrates upward to a gas collection apparatus. The liquid is reuptaken at an intake spot below the point at which it was diverted. It travels upward through a concentric chamber and subsequently reenters the tubing string at a point above that which it was diverted.
Multiple, self-adjusting downhole gas separator

Patent N° 5389128

This multiple, self-adjusting downhole gas separator includes an external decanting pipe having perforations about the periphery of that, and a concentric inner suction pipe equipped with inverted L-shaped suction pipe by-passes extending outwardly and downwardly from the periphery of the inner suction pipe. A plurality of respective retention cups are resiliently supported on the inner suction pipe by elastic elements. The retention cups are located in the space between the external decanting pipe and the inner suction pipe and are vertically spaced from each other with a respective L-
shaped suction cup by-pass extending into each retention cup. The lower end of the external decanting pipe is closed to define a decanting chamber into which the lower end of the inner suction pipe extends

**Figure A-39: Multiple, self-adjusting downhole gas separator**
(U.S. Patent № 5,389,128)

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**Downhole gas separator**

**Patent № 5333684**

This tool is provided for separating gas and water in a natural gas well. This separator is disclosed for use in recovering gas from a gas well without the production of water as well. The tool is part of the production tubing and includes a body defining and upper chamber, a lower chamber and a passage interconnecting the upper and lower chambers. The tool uses a member, such as plurality of vertically stacked balls which are lighter than water to close a channel when the water level exceeds a certain level. As gas
accumulates about the balls, the water level will be moved downwardly, eventually causing the balls to move out of engagement with the seal surface, opening the channel for passage of the gas upwardly for recovery. As the water level rises, the balls will again seal against the seal surface.

Figure A-40: Downhole gas separator (U.S. Patent N° 5,333,684)

Downhole gas separator for pump
Patent N° 5588486

A down-hole gas separator for a pump provides for the pumping of liquids from the lower portion of an inclined or horizontal passageway. The separator includes a nozzle for connecting to a pump inlet. The nozzle has an inlet and an outlet. The nozzle outlet is connected to the pump inlet. The separator is provided with means to cause the nozzle inlet to seek a lowermost position.
Downhole gas separator

Patent No 6179054

This is a slotted gas separator for a down hole pump has an internal baffle that is angled to push the oil down into the chamber and the gas up to be released. The baffle has a roughened surface area with small, grainy protrusions that result in a jagged, coarse surface to agitate the liquid-gas mixture and separate out any gas. The large surface area of the baffle insures maximum contact to separate the oil and gas. The gas is released through anchor ports on the top of the casing.
Gas separator for an oil well production line

**Patent N° 6322616**

This is a gas separator connectable between the seating nipple/pump and the mud anchor of a well production line takes advantage of gravitational, shear and centrifugal forces to detrain gas from the formation fluid. An outer cylindrical tube is concentrically secured by upper and lower couplings in relation to an inner cylindrical tube having an axial flow passage and a plurality of radial perforations. The upper coupling is adapted for connection to the seating nipple/pump and the lower coupling is adapted for connection to the mud anchor. The couplings each have a passage therethrough to extend the inner tube axial flow passage in fluid communication between the pump and the mud anchor. The outer cylindrical tube has a plurality of inwardly downwardly centrifugal oriented passages for admitting liquid entrained with gas into an annulus between the tubes and for causing the admitted liquid to flow in a downward spiral in the annulus.
The centrifugal oriented passages have irregular saw tooth surfaces extending inwardly downwardly and approximately tangentially in relation to the inner wall of the outer cylindrical tube so as to shear the gas from the fluid and centrifugal cause the gas to move inwardly and the oil and gas combinations to move outwardly in the annulus.

Figure A-43: Gas separator for an oil well production line

(U.S. Patent № 6,322,616)

Well-bottom gas separator
Patent № 6481499

This is a liquid/gas separator based on the effects of flows of the cascade and segregated types. It consists basically of a sedimentation vessel whose lateral surface has holes in the upper portion, enclosing a discharge pump, a suction pipe and the lower end of a production tubing. The vessel contains helicoidal surfaces for achieving segregated-type flow. A significant part of separation takes place above the level of the separator, in a medium in which there is a predominance of gas and the flow is in the form of a cascade.
Figure A-44: Well-bottom gas separator (U.S. Patent N° 6,481,499)
APPENDIX B

Description of the Separator Constructed

In this project, eleven kinds of separators were tested. Each separator has a different geometry. The description of the features of each downhole gas separator is posted in Tables B1-B5. Figure B-1 shows a drawing of a downhole gas separator which can be referred to when consulting tables B1-B5.

Tables B6 and B7 present the superficial liquid velocity in the separator and the superficial liquid velocity in the casing respectively for different liquid rates and separator models.

Table B1: Gas anchor features of all the gas separators tested in this project

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<th>OD AREA (inches^2)</th>
<th>ID AREA (inches^2)</th>
<th>LONGITUDE (inches)</th>
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Table B2: Dip tube features of all the gas separators tested in this project

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Table B3: Anchor port features of all the gas separators tested in this project

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Table B5: Annular area features of all the gas separators tested in this project

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Figure B-1: Downhole gas separator geometry
Table B-6. Superficial Liquid Velocity in the Separator

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Table B-7. Superficial Liquid Velocity in the Casing

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<th>PATTERSON 5 (INCHES/SEC)</th>
<th>PATTERSON 6 (INCHES/SEC)</th>
<th>PATTERSON 7 (INCHES/SEC)</th>
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APPENDIX C

Data Sheet Description

A spreadsheet is created for each series of tests (group of experiments between 6-9 tests) and includes the following information:

- Special model of the separator such as Patterson 1, Patterson 2, Patterson 3, Patterson 4, Patterson 5, Patterson 6, Patterson 7, Echometer 1, Echometer 2, Echometer 3 and Decentralized.
- Stabilized casing pressure (for this project, an average casing pressure of 5 and 10 psi is used for stabilized conditions).
- Separator position relative to the perforations in the casing (in front, under or above the ports).

The data obtained in the test follow the same format and are organized as such:

- The title of the spreadsheet corresponds to the model of separator that is being tested.
- The characteristics of the separator such as OD dip tube, number of anchor ports, and dimension of the anchor ports and the position of the separator.
- The date when tests were performed.
- A diagram in the upper right-hand corner of the spreadsheet shows the separator position relative to the perforations.
- Each table contains twenty-four columns and eighteen rows. The function of each column is described below:

  **Test number (Column 1):** All the tests are recorded by a digital video camera; hence, when comparing the data on the spreadsheet with the video in the Video Compact Disk, one needs to look at the number of the test and the date when the test was performed.
**Floco Meter (Column 2):** The liquid rate that is going into the well is measured by this flow meter. The recorded value is the number of seconds elapsed when 0.1bbl of liquid flows through the meter.

**Liquid rate (Column 3):** The factor of 8640 is divided by column 2 to convert from sec/0.1bbl to barrels per day.

**Gas Meter Reading (Column 4):** The gas (air) injected into the well is read by a Fisher & Porter meter. The scale of this flow meter is percentage of full scale, from 0% (0 MCFD) to 100% (16.42 MCFD).

**Gas Rate (Column 5):** The gas rate read in percentage in the fourth column is converted into the gas rate in MCFD units.

**Meter Pressure (Column 6):** The pressure at which the gas is measured in the meter is recorded in this column.

**Gas Rate at standard conditions (Column 7):** The gas rate calculated in the fifth column (at the pressure measured in column six) is converted to standard conditions using the general gas equation \( P_1V_1=P_2V_2 \). For this case:

\[
\text{Gas Rate (7th column)} = \frac{\text{Gas Meter Reading (5th column)} \times \text{Meter Pressure (6th column)}}{14.7}
\]

**Casing Pressure Maximum, Casing Pressure Minimum, Ports Pressure Maximum and Ports Pressure Minimum (columns 8, 9, 10, 11 respectively):** Due to the fluid in the well being a mix of water and air, the pressures have some fluctuations; therefore, the maximum and the minimum data are measured.

**Tubing Pressure Maximum and Tubing Pressure Minimum (columns 12, 13, 14 and 15):** Tubing pressure can be positive or negative (vacuum). These values depend on the drop pressure in the system. This parameter is very important in the
analysis of each separator model because the pressure drop is directly proportional to the geometry of the downhole gas separator.

**Superficial Liquid Velocity in Separator (Column 16):** Liquid rate calculated in column 3 is divided by the inside area of the diptube.

**Superficial Liquid Velocity in Casing (Column 17):** Liquid rate calculated in column 3 is divided by the inside area of the casing.

**Superficial Gas Velocity in Separator (Column 18):** Gas rate calculated in column 7 is divided by the inside area of the casing.

**Gas Rate through separator (column 19, 20, 21):** Three different kinds of flow meters for the registration of the gas rate through the separator are used in this project. Each of these flow meters reads a different range of rate, OMEGA FL-3820C (0 to 63 SCFD), OMEGA FL-3839ST (0 to 886 SCFD) and OMEGA FL 50000 (0 to 6480 SCFD).

**Gas Rate through separator (column 22):** The data obtained in columns 20, 21 or 22 are converted to MSCF.

**Comments (column 23):** Flow patterns, observations and anything special that will help in the later analysis is entered in this column.
Table C1: Spreadsheet where the measured and calculated data is saved

Date 7/21/2004

SEPARATOR TYPE: Patterson 1
OD DIP TUBE= 1"
NUMBER OF SLOTS=8
DIMENSIONS OF THE SLOTS=8" x 1/8"
FLUID ENTERING IN FRONT THE ANCHOR PORTS

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<th>Gas Rate Meter Reading</th>
<th>Gas Rate MCF</th>
<th>Gas Rate Pressure</th>
<th>Annulus Pressure Maximum</th>
<th>Annulus Pressure Minimum</th>
<th>Ports Pressure Maximum</th>
<th>Ports Pressure Minimum</th>
<th>Tubing Pressure Maximum</th>
<th>Tubing Pressure Minimum</th>
<th>Tubing Pressure Minimum</th>
<th>Superficial Gas Velocity in Separator</th>
<th>Superficial liquid Velocity in Casing</th>
<th>Gas Rate through Separator</th>
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APPENDIX D

Calculation of the Pressure Drop

The function of each column is described below:

**Qtestrate (Column 1):** The liquid rate that is going into the well is recorded in this column.

**V_diptube/anchor (Column 2):** The Qtestrate divided by the annulus area between the anchor and the diptube is the liquid velocity in the annulus anchor-diptube.

**P1 (Column 3):** The pressure at the anchor ports is recorded in this column.

**Re_diptube/anchor (Column 4):** The Reynolds Numbers for the annulus area between the anchor and the dip tube is calculated by:

\[
N_{Re_{dip tube/anchor}} = \frac{De \cdot \rho \cdot V_{dip tube/anchor}}{\mu}
\]

\(\rho\) and \(\mu\): These are the density and the viscosity of the fluid in the annular area (anchor-dip tube), in our case is water.

**V_diptube/anchor:** This is the superficial liquid velocity calculated in column 2.

**De = Diameter equivalent of the annular area, this is calculated by:**

\[
De = 0.8165(D_2 - D_1)
\]

where \(D_1\) is the annulus ID and \(D_2\) is the annulus OD. For this case \(D_1\) is the diptube OD diameter and \(D_2\) is the anchor ID diameter.

**ffactor_diptube/anchor (Column 5):** This is the friction factor, calculated by the Chen equation:

\[
\frac{1}{\sqrt{f_{dip tube/anchor}}} = -4 \log \left\{ \frac{\epsilon}{3.7065} - \frac{5.0452}{N_{Re_{dip tube/anchor}}} \log \left[ \frac{\epsilon}{2.8257} + \left( \frac{7.149}{N_{Re_{dip tube/anchor}}} \right)^{0.8981} \right] \right\}
\]
ε: This is the roughness of the pipe. In our case, because the casing, the dip tube and the anchor is very smooth, it is used for roughness as 0.0000001 for all the friction factors.

**P4 (Column 6):** This is the pressure at the dip tube entrance that is calculated by:

\[ P4 = P1 + \frac{2 f_{dip tube/anchor} \rho L V_{dip tube/anchor}}{De} + \rho g L \]

where \( L \) is the dip tube length

**V_{dip tube} (Column 7):** The liquid rate divide by the area inside the diptube.

**Re_{dip tube} (column 8):** This is the Reynold Number for the dip tube, calculated by:

\[ N_{Re_{dip tube}} = \frac{D \times \rho \times V_{dip tube}}{\mu} \]

\( D \): Inside diameter of the diptube
\( \rho \) and \( \mu \): These are the density and the viscosity of the fluid inside the dip tube, in our case is water.

**V_{dip tube}:** This is the superficial liquid velocity calculated in column 7.

**ffactor_{dip tube} (column 9):** This is the friction factor, calculated by the following formula:

\[ \frac{1}{f_{dip tube}} = -4 \log \left\{ \frac{\varepsilon}{3.7065} - \frac{5.0452}{N_{Re_{dip tube}}} \log \left( \frac{\varepsilon^{1.1098}}{2.8257} + \left( \frac{7.149}{N_{Re_{dip tube}}} \right)^{0.8981} \right) \right\} \]

**V_{tubing} (Column 10):** The liquid rate divide by the area inside the tubing.

**Re_{tubing} (column 11):** This is the Reynold Numbers for the tubing, calculated by:

\[ N_{Re_{tubing}} = \frac{D \times \rho \times V_{tubing}}{\mu} \]

\( D \): Inside diameter of the tubing.
ρ and μ: These are the density and the viscosity of the fluid inside the tubing, in our case is water.

\( V_{\text{tubing}} \): This is the superficial liquid velocity calculated in column 10.

**\( ffactor_{\text{tubing}} (\text{column 12}) \):** This is the friction factor, calculated by the following formula:

\[
\frac{1}{\sqrt{f_{\text{tubing}}}} = -4 \log \left[ \frac{\frac{\varepsilon}{\rho}}{3.7065} - \frac{5.0452}{N_{\text{Re,tubing}}} \log \left( \frac{\frac{\varepsilon}{\rho}}{2.8257} + \left( \frac{7.149}{N_{\text{Re,tubing}}} \right)^{0.8981} \right) \right]
\]

\( \frac{1}{2} \rho \Delta V^2 \text{(psi)} \): This is the kinetic energy.

\[
\text{Kinetic} = \frac{1}{2} \rho \Delta V^2 = \frac{1}{2} \rho \left( V_{\text{tube}}^2 - V_{\text{dip tube}}^2 \right)
\]

**\( P3 (\text{Column 14}) \):** This is the pressure at the dip tube exit

\[
P3 = P4 - \frac{2 f_{\text{dip tube}} \rho L V_{\text{dip tube}}^2}{D_{\text{dip tube}}} - \rho g L + \text{Kinetic}
\]

**\( P2 \text{ calculated (Column 15)} \):** This is the pressure in the pump calculated by:

\[
P2 = P3 - \frac{2 f_{\text{tube}} \rho L V_{\text{tube}}^2}{D_{\text{tube}}} - \rho g L
\]

where \( L \) is the tubing length
Table D1: Spreadsheet for calculation of the pressure drop

<table>
<thead>
<tr>
<th></th>
<th>Qleakrate</th>
<th>Vdip tube/anchor</th>
<th>P1 (psi)</th>
<th>Redip tube/anchor</th>
<th>ffactordip tube/anchor</th>
<th>P4 (psi)</th>
<th>Vdip tube</th>
<th>Redip tube</th>
<th>ffactordip tube</th>
<th>Vtube</th>
<th>Re tube</th>
<th>ffactortube</th>
<th>1/2 ρ*ΔV^2 (psi)</th>
<th>P3 (psi)</th>
<th>P2 (psi)</th>
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</table>
NOMENCLATURE

A  Area
BG  gas formation volume factor (volume of gas per barrel of oil scf/stbl)
BO  oil formation volume factor (in situ bbl of oil/stb)
BW  water formation volume factor (in situ bbl of water/stb of oil)
CW  water cut (stb of water/stb of oil)
da  vector of magnitude da
DBC  distance between the pipes centers (inches)
DC  inner diameter (inches)
De  diameter equivalent of the annular area (inches)
D_{EP}  equi-periphery diameter (inches)
DT  outer diameter of the inner pipe (inches)
e  Eccentricity
E_{G,L}  average volume fraction of gas and liquid phases
EV  volumetric efficiency of the pump
f_{CA}  friction geometry parameter for concentric annulus
f_{EA}  friction geometry parameter for eccentric annulus
fF  fanning friction factor
FR_{g}  the gas Froude number
f_{XA}  fanning friction factor
g  gravity acceleration (ft/sec^2)
gc  dimension conversion factor=32.2 lbmft/lbfsec2
GOR  gas oil ratio (scf/b, or acf/b for in situ gor)
M  mass flow rate (lb/second)
N_{Re}  Reynold number
P  Pressure (psi)
Pc  casing pressure (psig)
P_{1}  pressure at the anchor ports (psig)
P_2 \quad \text{pressure in the pump (psig)}

P_3 \quad \text{pressure at the diptube exit (psig)}

P_4 \quad \text{pressure at the dip tube entrance (psig)}

q_\alpha \quad \text{volumetric flow rate of the lighter phase in two-phase flow situation (ft}^3/\text{second)}

q_\beta \quad \text{volumetric flow rate of the denser phase in two-phase flow situation (ft}^3/\text{second)}

Rs \quad \text{solution gas (scf/b)}

T \quad \text{Temperature (°F)}

\overline{u}_\alpha \quad \text{average in-situ velocities for the lighter phase in two-phase flow situation (meters/second)}

\overline{u}_\beta \quad \text{average in-situ velocities for the denser phase in two-phase flow situation (meters/second)}

V \quad \text{Velocity (inches/second)}

V_{0,\infty} \quad \text{bubble rise velocity in an infinite media (inches/second)}

V_G, V_L \quad \text{superficial gas and liquid velocity (inches/second)}

V_M \quad \text{mixture superficial velocity (inches/second)}

V_{SG} \quad \text{superficial gas velocity (inches/second)}

V_{SL} \quad \text{superficial liquid velocity (inches/second)}

y_\alpha \quad \text{holdup of the lighter phase in two-phase flow situation}

y_\beta \quad \text{holdup of the denser phase in two-phase flow situation}

\textbf{Greek symbols}

\alpha \quad \text{lighter phase in two-phase flow situation}

\beta \quad \text{denser phase in two-phase flow situation}

\rho \quad \text{density}

\sigma \quad \text{surface tension}
**Subscripts**

C  casing  
G  gas  
L  liquid  
M  mixture  
P  pump  
T  tubing

**Abbreviations**

°C  Celsius degrees  
°F  Fahrenheit  
bbbl/day  barrels per day  
BBD  Barrels per day  
BHP  bottom hole pressure  
DGS  downhole gas separator  
ESP  electro submersible pump  
ft  feet  
ft²  square feet  
“Hg  inches of mercury  
ID  inside diameter  
in  inches  
in²  square inches  
OD  outside diameter  
Kg/m³  kilograms per cubic meter  
m/s  meter per seconds  
MCFD  thousand standard cubic feet per day  
mm  millimeters  
PCP  progressing cavity pumps
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<td>psi gage</td>
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References


Wilson, B.L.: “ESP Gas Separator’s Affect on Run Life,” SPE 28256

www.glossary.oilfield.slb.com

http://en.wikipedia.org/wiki/Main_Page
VITA

Omar Lisigurski was born in Lima, Peru on May 18, 1975. He received a Bachelor of Science degree in Petroleum from the National University of Engineering of Lima – Peru (UNI) in 1997.

He has held engineering internships with Petroperu (1996), Perupetro (1996) and Occidental Petrolera del Peru Inc. (1997).

He studied in a postgraduate program at the Technology Institute at Buenos Aires (ITBA) in 1999.

In Peru, Mr. Lisigurski worked in both offshore and onshore drilling operations at Schlumberger (1998) and as a supporting and consulting engineer with Unipetro ABC, Inc. (1998-1999 and in 2002). At Repsol-YPF in Argentina (1999-2002), he worked as a production and reservoir engineer.

He began graduate studies at the University of Texas at Austin in January 2003. Since spring 2003, Mr. Lisigurski has been a research assistant with the Department of Petroleum and Geosystems Engineering.

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