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A Study of a Novel Down-hole Gas-Liquid Separator/Connector

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A Study of a Novel Down-hole Gas-Liquid Separator/Connector

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Abstract

A Study of a Novel Down-hole Gas-Liquid Separator/Connector

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The University of Texas at Austin, 2018

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Production from shale in the United States has drastically increased the overall domestic oil production. This was achievable due to the advances in horizontal well drilling and hydraulic fracturing technology, which gave access to new reservoir rock. In addition, as wells declined in rate, artificial lift methods like the use of a beam pump, electric submersible pump (ESP), or gas lift physically helped bring the oil and gas to surface and extended the life of a well. Operational challenges such as containing costs to maintain ESPs and using beam pumps on high gas wells became significant factors in determining the economic viability of a well.

In this study, we examined a method to improve oil and gas separation down-hole in the production tubing so that a beam-pump will lift primarily liquid to the surface. Simultaneously, the method ensures that an ESP will remain effective and not overheat, as reservoir pressure declines, to lift fluid to the depth of the separator. A gravity-based down-hole gas liquid separator/connector was constructed using three acrylic pipes, one set inside another, with the inner pipe intended to tie in to the production tubing. The outer two pipes acted together as a gravity separator and pump connector. Water and air was pumped at varying rates from the bottom to simulate the fluid an ESP would deliver to the separator/connector. A standing valve was built into the inner tube, and a rod with traveling valve was manually operated to simulate a beam pump. The water and air mixture was visually inspected inside the pump to determine the effectiveness of the separator. The point at which the separator will fail to keep gas bubbles larger than 0.25 inches from coming inside the pump was quantified using three function tests:

1) Allowable Gas-Liquid Ratio the separator will process
2) Liquid Velocity falling down the middle tube of the separator
3) Annular Gas Superficial Velocity between outside and middle tube

After testing a variety of air/water rates through two different sized separators, the results showed that if a separator passed all three function tests for a given air/water rate, then it would successfully separate bubbles larger than 0.25 inches from coming into the pump.

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SECTION 1 – INTRODUCTION TO THE SEPARATOR/CONNECTOR

For the past decade, energy companies in the United States predominantly focused on drilling horizontal oil and gas wells in tight shale rock formations. All wells gradually decline in production rate as the reservoir is depleted, but horizontal wells drilled in shale formations have a unique characteristic of rapid initial decline rate. For this reason, horizontal wells spend a large portion of their life producing at a low rate. This study on a downhole gas liquid separator is specifically applicable to those horizontal wells in the latter stage of their life, producing at a low rate.

Background:

Our separator/connector is designed to be a part of the production tubing string, positioned at a calculated depth. The reservoir is initially high pressured, so the fluid flows up the production tubing to the surface naturally at a high rate. After some time and depletion, a beam pump or electric submersible pump (ESP) is used to assist in lifting the fluid to the surface, as the reservoir pressure is not sufficient acting alone. During this time, we experience low flow rates.

The purpose of this experimental study was to address two main problems identified in the industry associated with low flow-rate wells:

Problem 1: Low flow rate horizontal wells with beam pumps in the vertical section of the well continue to struggle due to gas making its way into the pump. First, the current down-hole gas-liquid separation method, such as the use of a dip-tube beneath the pump, may not be effective. Gas inside the pump decreases the pump volumetric efficiency as the pump now must process that volume of gas. Second, when used in the vertical portion of a horizontal well, the intermittent unloading of liquid from the horizontal further complicates the ability of the down-hole gas-liquid separator to function. Gas in the pump shortens the life of beam lift equipment through valve chatter and decreases the efficiency of the system:

Problem 2: Additionally, for low flow-rate wells, operators may try to use an electric or hydraulic pump set deep in the horizontal to lift the fluid to the surface, rather than using a beam pump. The intention is to increase the reservoir flow rate by maximizing the pressure draw down in the reservoir. However, as the well declines in flowrate and pressure, these pumps may not create the discharge pressure necessary to flow liquid to the surface. In this case, the pump ceases to function.

By creating a down-hole gas-liquid separator intended to be placed at a depth at which fluid can be successfully lifted to by some electrical (ESP) or hydraulic pump, the problems mentioned above can be minimized in tandem. In low flow rate wells, the downhole gas-liquid separator’s primary purpose is to separate oil from gas for the beam pump, but will also act as a pump “connector” between a beam pump and ESP, which is assumed to be the lower pump. The separator/connector is best utilized on a low-flowrate well with a pump jack on surface and an ESP set in the deepest possible position in the horizontal. If the lower pump is placed at such a location it allows the horizontal part of the well to act as a gas-liquid separator where the liquid collects in the deepest part of the lateral.

As fluid is pumped by the ESP to the separator/connector (see Figure 4, p. 9), separation of liquid from gas occurs so long as the separator dimensions satisfy the design requirements for adequate separation. This separation will reduce the gas intake into the pump of the beam lift, even though not all the gas can ever be separated. The majority of the produced gas flows up through the casing-tubing annulus. The separator/connector's design allows the separated liquid to be stored in the middle tube (see Figure 5, p. 9) until the beam pump lifts the liquid to the surface. As reservoir flow rate declines, the intermittent beam pump rate can be more easily matched to reservoir flow rate because the middle tube acts as a container for the continuously separated liquid. Whatever liquid is not lifted by the beam pump on the first upstroke will be waiting in the middle tube for the following stroke. In this way, the inadequate lifting capability from an ESP is addressed with the placement depth of the separator/connector working together with a beam lift which has minimal gas intake.

In this way, the ESP can maximize the reservoir flow rate by making the pressure draw down in the reservoir as large as possible and the beam pump can take over at the depth where the ESP discharge pressure is exhausted and lift the liquid to the surface. This combination creates the largest flow rate out of the reservoir while minimizing the size and the cost of the lift equipment. The use of the pump connector makes this possible and acts to separate the last of the gas entrained in the flow from the ESP improving the overall system efficiency.

Currently Available in Industry

The separator/connector proposed in this study is unique to a scenario in which an ESP is used near the toe of a horizontal well, and a beam pump is operated from the surface. In many cases, a beam pump operates solely with some type of gas separation mechanism located directly beneath the pump. The following are some examples of gas separation mechanisms that operators have chosen to use in the past.

Poor Boy Gas Separator

Setting the pump below the formation perforations is an ideal scenario, where the fluid coming from the reservoir is forced to fall down to the anchor perforations and the gas naturally travels up in the annulus. But this is more prevalent in vertical wells where it is possible to have the beam pump located below the formation perforations. Many times, it is not possible or desirable to set the beam pump below formation perforations, such as for horizontal wells. A Poor Boy Gas Separator is common for those wells where the pump intake is above the perforations.

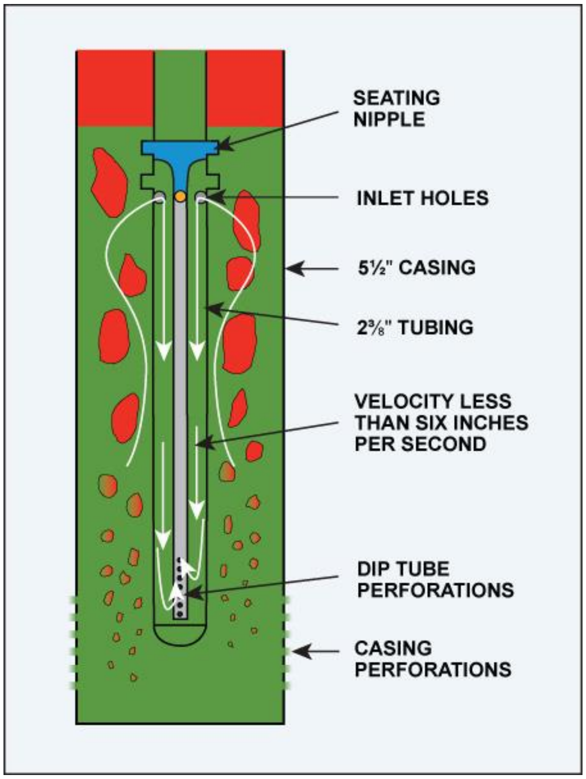


Figure 1 - Poor Boy Separator (Bommer and Podio, 2015)

Figure 1 is a schematic of a poor boy separator, taken from The Beam Lift Handbook (Bommer and Podio, 2015). These separators are typically constructed using the materials available at the well site, so every separator is slightly different. At the top, inside the 2 3/8" tubing is where the pump will be positioned. A perforated tubing pipe is attached below the seating nipple, which acts as inlet holes for the liquid to fall down towards the dip tube perforations. The dip tube is typically 20 – 30 ft long and is connected to the pump intake. The design allows for fluid coming in from the casing perforations to first, naturally separate liquid from gas. As the gas expands and surfaces, the goal is to have only liquid make its way down the inlet holes of the tubing, towards the dip tube.

Packer Separator

The packer separator is most like the separator/connector analyzed in this study because it uses the casing-tubing annular area for separation. As seen in Figure 2, the packer acts as a seal such that produced fluids flow up inside the small diameter riser and out into casing-tubing annulus. The gas continues upward and is produced at the casing head, while the liquid enters an opening at the bottom which feeds into the pump intake. Because of the narrow riser used for the produced fluids to flow up, the presence of produced solids, paraffin, and scale inhibits the use of this type of separator.

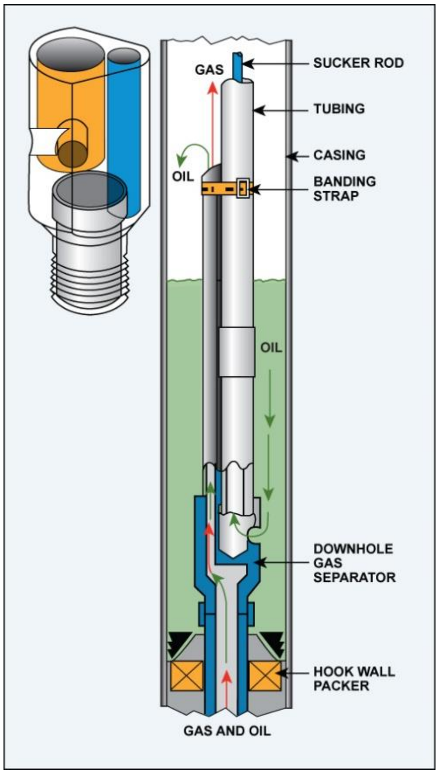


Figure 2 - Packer Separator (Bommer and Podio, 2015)

Texas Twister Separator

Several designs of separators have been patented that make use of the rotational motion of the fluids in the annulus between the dip tube and separator shell. The Texas Twister, shown in Figure 3, has a spiraled dip tube, which induces a rotational velocity on the liquid-gas mixture flowing down through the entry ports (Bohorquez et al). The inertial forces act to move the denser fluid to the outer zone, and gas to the inner zone. The more dense liquid makes its way down to the entry of the dip tube while the gas from the inner zone floats up to exit the ports into the well annulus. This design is very similar to the poor boy separator, except that the dip tube is helical shaped. This helical shape allows the Texas Twister to process a significantly higher flow rate coming from the reservoir compared to the poor boy separator.

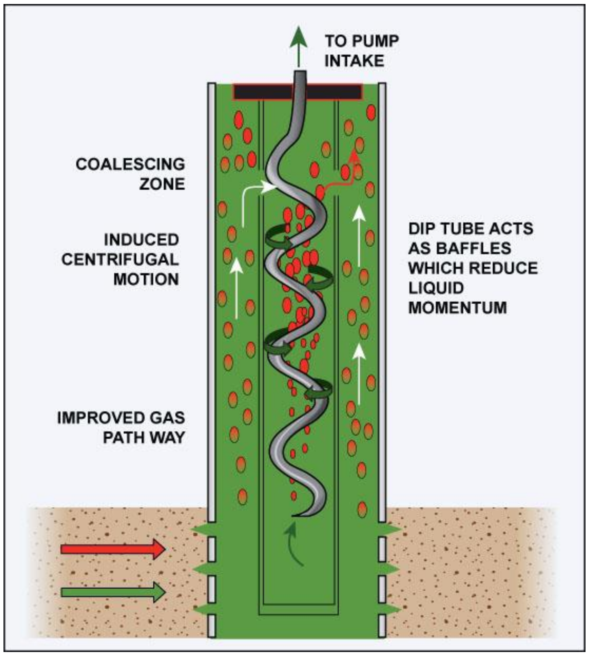


Figure 3 - Texas Twister Separator (Bommer and Podio, 2015)

The designs mentioned above highlight the gas separators where the pump is set above the perforations and typically act solely with the beam pump to lift liquid to the surface. The separator/connector in this study is gravity based and does not incorporate a dip tube below the pump. Chapter 10 of The Beam Lift Handbook outlines many other gas separator designs applicable to various scenarios.

SECTION 2 – EXPERIMENT SETUP

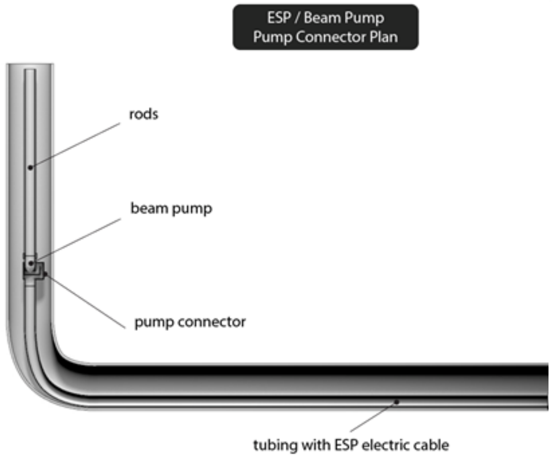


Figure 4 – Big Picture View of Separator

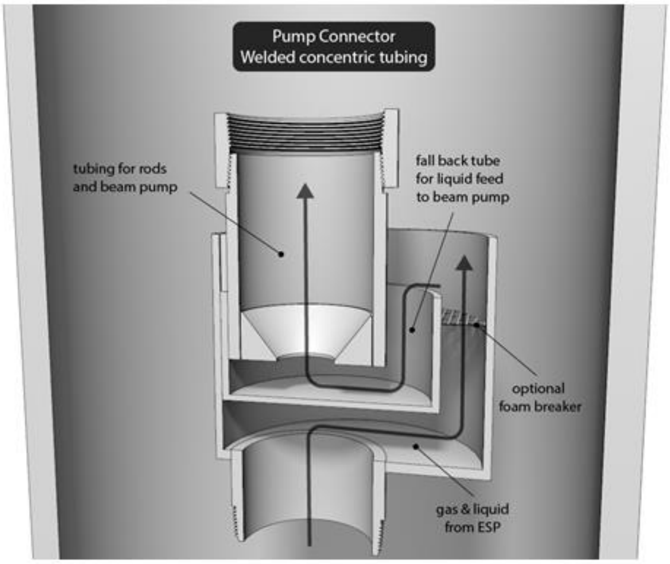


Figure 5 – Separator/Connector 3-D view

Figure 5 shows the down-hole separator/connector with fluid to enter from the bottom of the outside tube and fill up to the point of overflow into the middle tube. Gas will separate from liquid during the flow down the middle tube and the gas exits the open top of the separator. The fluid that enters the middle tube now also enters the pump intake which is inside the tubing connector to the surface. While it is desirable to pump all the liquid entering the separator (liquid contained in the middle tube), if any liquid overflows the device (in the case of high reservoir flow rates, with low rod lift stroke speeds), it simply returns to the bottom of the well to be flowed back into the separator again.

If the device is used as a pump connector also, it is placed in the tubing as shown in Figure 4. In this orientation, the device serves as a separator and connects the discharge of, in this case an electric submersible pump (ESP), to the intake of a beam pump. This is useful when low volumes of liquid are lifted by a small ESP. These types of pumps typically do not have enough stages to create sufficient discharge pressure to flow to the surface from a deep well. As shown in Figure 4, the ESP is placed at the low point in a horizontal well and connected to the beam lift at a point where the ESP discharge pressure is exhausted and the beam lift takes over to produce the liquid to the surface. The connector will work with any combination of pumps, so long as the bottom pump is driven electrically or hydraulically.

The design of the connector or separator is such that the largest tube that will fit in the casing is used as the outside tube. The middle tube is the largest size that will fit inside the outer tube and the inner tube is a standard tubing dimension to connect to the surface. Several examples are given in Table 1.

Table 1 – Example Separator Sizes

	Separator/Connector Dimensions								Pump Intake	Max Liquid
Casing	Outside Tube			Middle Tube			Inside Tube		Volume	Rate
OD (in)	OD (in)	ID (in)	Length (ft)	OD (in)	ID (in)	Length (ft)	OD (in)	ID (in)	(Bbl)	(Bbl/Day)
4.5/11.6	3.5	3	32	2.75	2.5	29	2.375	2	0.017	25.6
5.5/17 ppf	4.5	4	32	3.5	3.25	29	2.375	2	0.139	206.5
7/29 ppf	5.5	4.95	32	4.5	4	29	2.875	2.441	0.218	324.5

Table 2 provides the corresponding volumes and flow areas for the example separator/connectors listed in Table 1. Pump intake volume, total flow area, and separator volume will be used to determine the capacity of the separator, described in Section 3.

Table 2 –Areas and Volumes for Separators corresponding to Table 1

Separator/Connector Dimensions								Pump Intake	Total Flow	Separator
Outside Tube			Middle Tube			Inside Tube		Area	Area	Volume
OD (in)	ID (in)	Length (ft)	OD (in)	ID (in)	Length (ft)	OD (in)	ID (in)	(sq in)	(sq ft)	(cu ft)
3.5	3	32	2.75	2.5	29	2.375	2	0.479	0.011	0.324
4.5	4	32	3.5	3.25	29	2.375	2	3.866	0.047	1.372
5.5	4.95	32	4.5	4	29	2.875	2.441	6.074	0.065	1.896

Connector/Separator Length: In addition to using the largest tubes that will fit into the casing, the length of the connector should be determined based on the output of the pump lifting the liquid to the surface. A longer length provides extra volume that is held inside the middle tube that can be pumped if fluids are produced intermittently from the pump or intake below. A convenient length is the length of a standard joint of tubing, about 33 feet long. The volume that can be held inside the middle tube of a connector this long is shown in Table 1 as the pump intake volume. The number of plunger strokes that can be held inside the connector if it is full is the inside volume from Table 1 divided by the pump displacement per stroke. For example, if the 5.5” connector is used with a plunger that displaces 0.018 bbl/stroke (1.5” plunger with a 100” stroke) the connector can hold a volume that is equal to 12 pump strokes.

If larger flow rates or gas-liquid ratios are expected, the separator can be made longer.

Construction:

For conducting experiments, two separators were constructed using acrylic pipe – one large, and one small. The dimensions and corresponding metrics are presented in Table 3 and Table 4. Acrylic pipe is transparent and allows us to see how water and air mix and travel upwards in the annulus, and then drop down the middle tube. The bubbles that make their way into the pump (inner tube) can also be visually seen and measured.

Large separator:

Table 3 – Large Separator Dimensions

Separator/Connector Dimensions							
Outside Tube			Middle Tube			Inside Tube	
OD (in)	ID (in)	Length (ft)	OD (in)	ID (in)	Length (ft)	OD (in)	ID (in)
6	5.5	6	4.5	4	4	3	2.5

Pump Intake Volume (Bbl)	Pump Intake Area (sq in)	Total Flow Area (sq ft)	Separator Volume (cu ft)	Outside Ann. Area (sq in)
0.0272	5.50	0.0927	0.371	7.85

Small separator:

Table 4 - Small Separator

Separator/Connector Dimensions							
Outside Tube			Middle Tube			Inside Tube	
OD (in)	ID (in)	Length (ft)	OD (in)	ID (in)	Length (ft)	OD (in)	ID (in)
3.25	3	5	2.75	2.5	3	2.375	2.125

Pump Intake Volume (Bbl)	Pump Intake Area (sq in)	Total Flow Area (sq ft)	Separator Volume (cu ft)	Outside Ann. Area (sq in)
0.00178	0.479	0.0112	0.0335	1.13

Experiment Parts Used:

Figure 6 below shows all of the major parts used in the experiments. Each part is numbered and described in more detail.

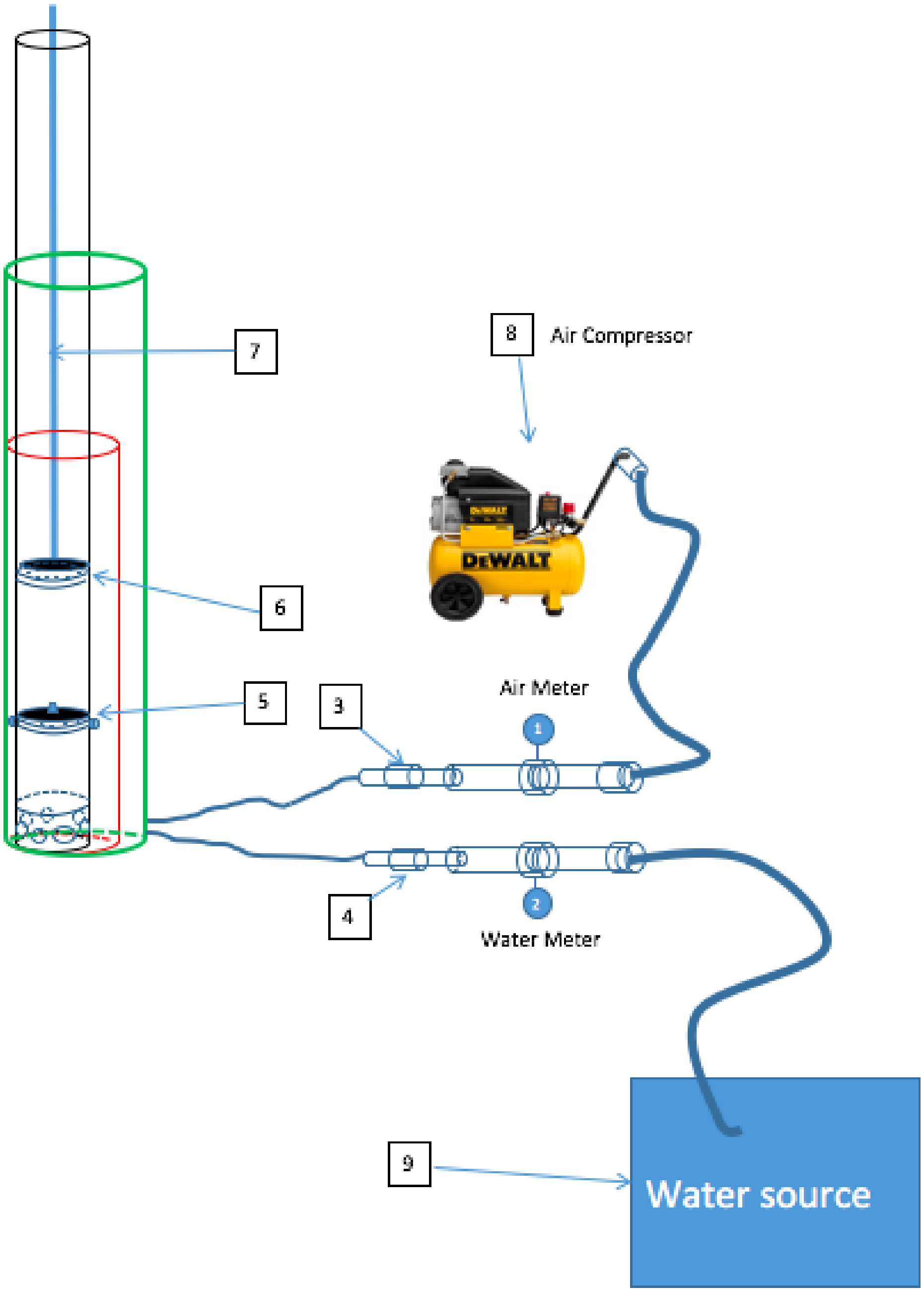


Figure 6 - Experiment Parts Used

1) The air meter that was initially used was a mass flow meter made by Omega Engineering, with a measurement range of 0 – 500 Liters/min. This meter was predominantly used with the smaller separator. A wired power source was used to turn on the instrument. To prevent any water from touching the electric source, a plastic bag was used to isolate the outlet plugs. After constructing the larger separator, this meter was upgraded to the larger version made my Omega Engineering, which had a measurement range of 0 – 1000 Liters/min.

Figure 7 - Air Meter

2) The water meter used in this experiment was also made by Omega Engineering, with a measurement range of 0 – 15 gallons/min. The meter was battery powered.

Figure 8 - Water Meter

3) A gas check valve was used on the air line to prevent any fluid flow from going backward through the meter. The valve used was a ¾" Strataflo No. 300, with a working pressure of 400 psi. A minimum upstream (cracking) pressure of 1 – 2 Lbs. is required to operate.

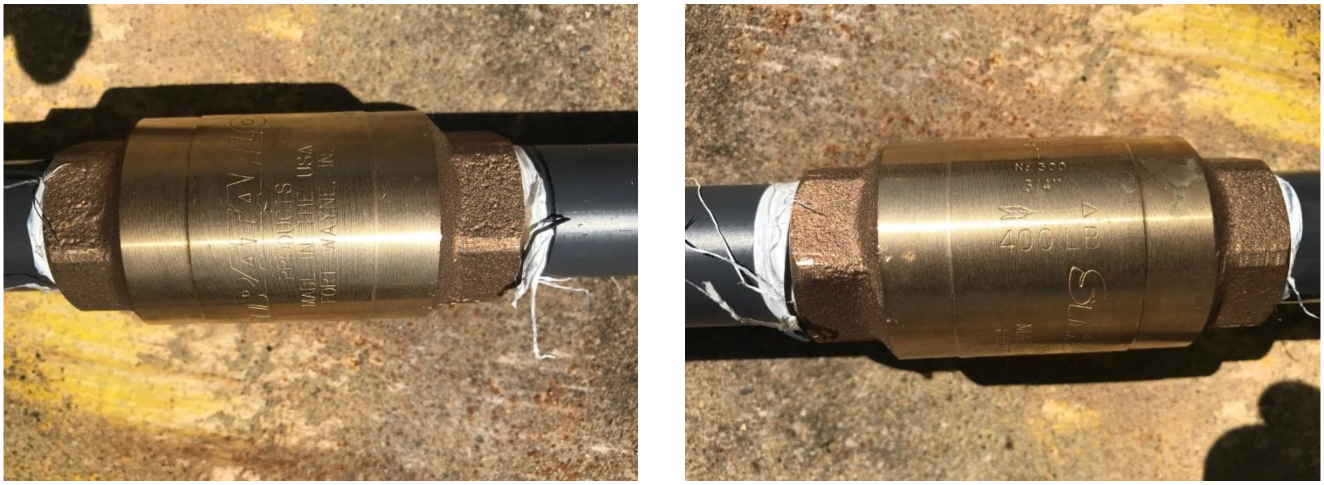


Figure 9 - Air Pathway Check Valve

4) A water check valve was also used for the water line to prevent any fluid flow from going backward through the meter. The experiments made use of a 1” Hayward True Union Ball Check valve.

Figure 10 - Water Pathway Check Valve

5) The standing valve is used as part of the design of the pump. It is constructed using a plastic disc with holes which allow fluid flow through. A rubber flapper is screwed on top of the plastic disc to prevent any fluid from going back down. The plastic disc is bolted on to the inside acrylic pipe so it is immobile. During the upstroke, the rubber flapper bends upward along the outer edge which allows fluid to come up into the pump, and stays attached to the plastic disc in the middle. On the down-stroke, the rubber flapper prevents any fluid flow down so that it may enter the traveling valve, which is attached to the moving rod.

Figure 11 - Standing Valve

6) The traveling valve was constructed similar to the standing valve, except that it is attached to the rod. The plastic disc with holes has a flapper attached on top. During the down-stroke, the valve moves with the rod and the rubber flapper bends upward along the outer edge which allows fluid to enter the pump. On the up-stroke, the rubber flapper allows the fluid to be lifted up. The traveling and standing valve act together like to create an effect like a plunger.

Figure 12 - Traveling Valve

7) The rod used is a ½" solid metal bar with a handle at the top. The handle was used to assist with the lifting of the rod weight plus the fluid it was carrying. At the bottom end is the traveling valve where the fluid being lifted would sit on top of.

Figure 13 - Metal Rod

8) The air compressor used to supply the air rate for all the experiments was a 2 stage, 3 phase, 5 HP Speedaire industrial compressor. This device supplied a maximum rate of approximately 520 Liters/min.

Figure 14 - Air Compressor

9) The water source for the all the experiments was supplied from a tap. The water output range is regulated by the city at a maximum of 10.5 gallons/min.

Figure 15 - Water Source

SECTION 3 – THE SEPARATOR/CONNECTOR PHYSICS – HOW IT WORKS

Our separator design is derived from the fundamental Stokes' Law (Equation 1, p. 25), which describes a spherical grain settling through a fluid at a given Reynold's number. The spherical grain undergoes a downward-directed force of gravity, an upward-directed force of buoyancy, and an upward-directed force of fluid drag, which tends to retard the downward settling of the grain. Similarly, a gas bubble which is submerged in liquid is subjected to viscous drag and gravity acting downward, and buoyancy acting upward, as the bubble flows its way to the surface. The moving gas bubble has a net upward velocity defined as the gas bubble slip velocity. Slip velocity is the difference between flow in one direction minus flow in the other direction. Bubbles with smaller diameters have lower slip velocities as buoyancy is drastically reduced for smaller bubbles.

Bubble Slip Velocity and Bubble Size

Figure 16 shows laboratory measurements of bubble slip velocity as a function of bubble size and viscosity of liquid the bubble is submerged in. The diagram indicates that the velocity of a bubble moving upwards in stationary fluid for a select bubble size decreases as fluid viscosity increases. The trends seen for water, glycol, and glycerin + water (1cp to 110cp) represent the majority of oil well pumping operations.

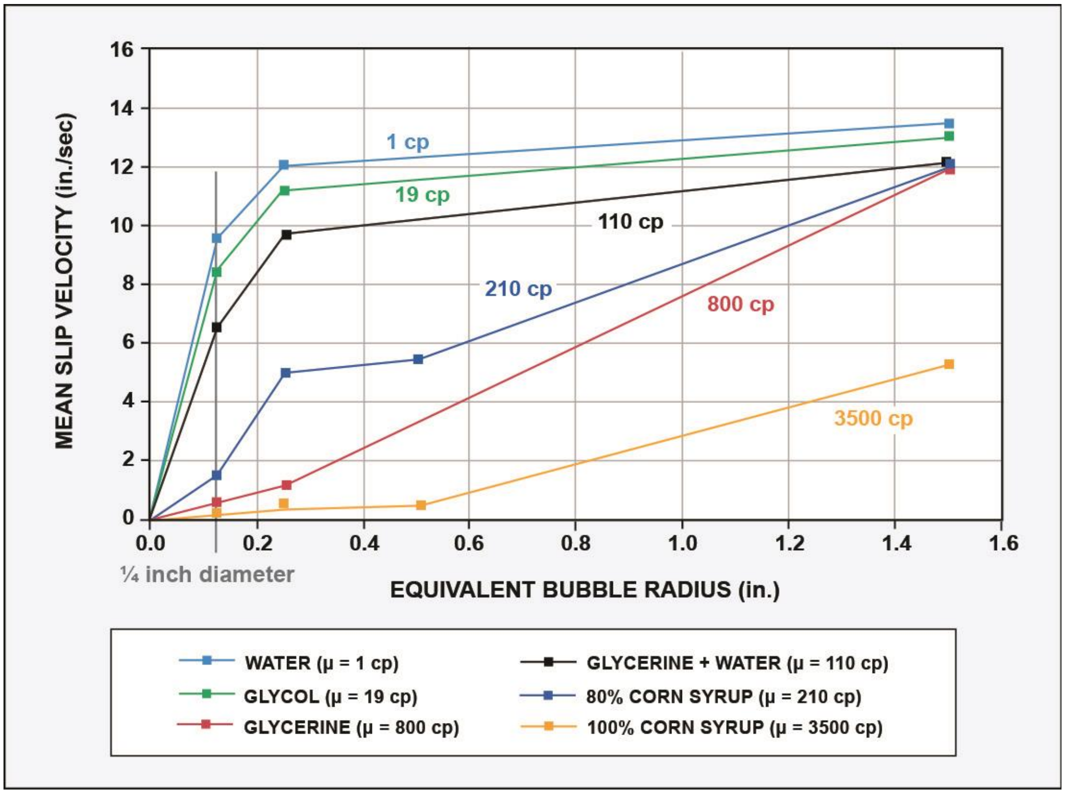


Figure 16 - Air bubble slip velocities (Bommer and Podio, 2015)

In this application of creating a gravity based down-hole gas-liquid separator, the liquid-gas mixture is flowing up the annulus and continuously overflowing into the middle tube, where all gas bubbles are attempting to reach the surface. If the liquid velocity falling on top of the gas bubbles in the middle tube is lower than the gas bubble slip velocity (dependent on bubble size), then it is expected that those gas bubbles will make their way to the surface, and be separated from the liquid. For this reason, a practical gas separator design must include defining the minimum bubble size diameter to be separated from the liquid, as 100% gas separation from liquid is not possible because liquid is continuously moving. In other words, a separator must specify the bubble size diameter above which will be guaranteed to separate, and below which could remain in the liquid, and be fed to the pump.

Historically, a ¼ inch diameter has been selected as the smallest bubble desired to be separated from the liquid. Correspondingly from Figure 16, a conservative 6 in/sec slip velocity can be used as a standard to design the liquid capacity of a gravity separator, which influences liquid velocity down the middle tube. A larger liquid capacity separator (larger cross sectional area where bubbles separate) will allow a higher liquid rate into the separator, simultaneously having a lower liquid velocity flowing down the middle tube.

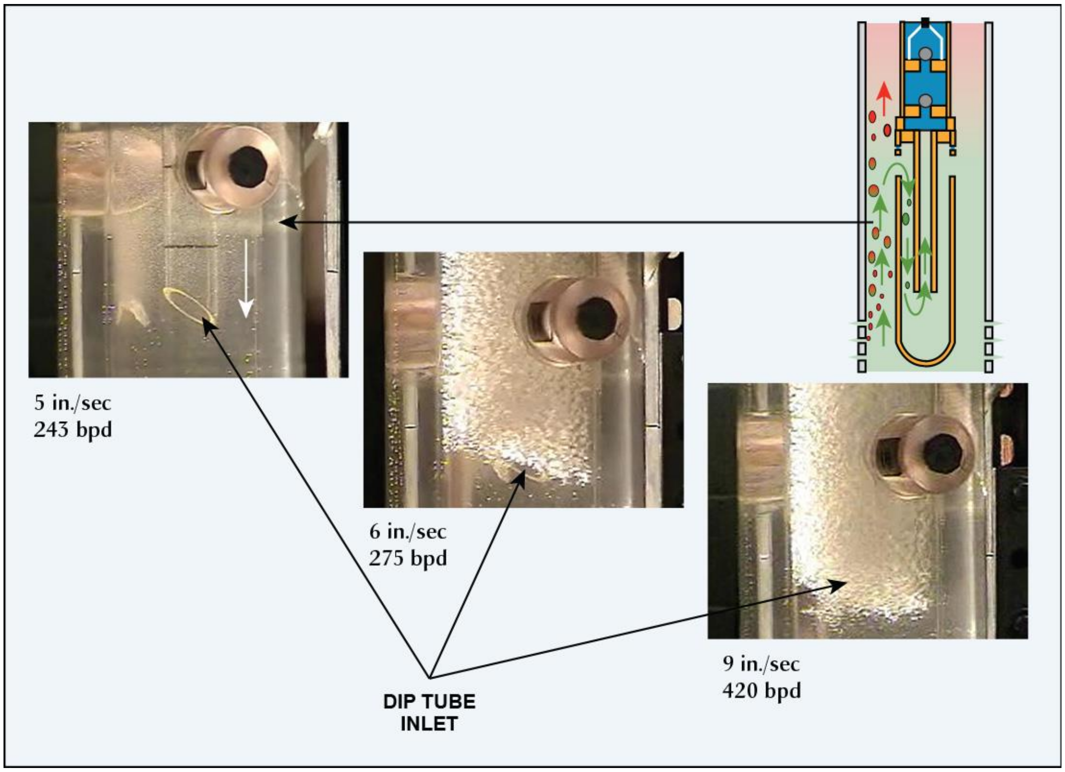


Figure 17 - Bubbles and Liquid Velocity comparison (Bommer and Podio, 2015)

Figure 17 shows an example of a dip tube method separator constructed by Robles, 1996, presented in The Beam Lift Handbook. The liquid capacity of this separator is such that 275 bpd yields a 6 in/sec velocity of liquid flowing down the mud anchor, as seen in green arrows.

According to Figure 16, if we desire a bubble diameter no larger than 0.25 inches to be allowed inside the pump, then the conservative 6 in/sec liquid velocity down the middle tube is reached when the flowrate up the annulus is 275 bpd. Figure 17 shows that for a flowrate of 243 bpd, the 0.25 inch bubbles are suspended above the dip tube entry, and make their way to the surface because the velocity of the liquid pushing down on the bubbles (4 in/sec) is less than the 6 in/sec gas bubble slip velocity. Similarly, for a flowrate of 420 bpd, bubbles are pushed down past the dip tube because the velocity of liquid flowing down is larger (9 in/sec) than 6 in/sec gas bubble slip velocity.

Calculate Separator Dimensions

The objective of this section is to determine the gas and oil volumes that a given separator dimension can process. The design equations shown in this section are general and therefore would apply to any separator.

Gas Capacity Equation:

$$v_g = \frac{18.49{d_g}^2\,(\rho_l - \rho_g)}{\mu_l} \tag{1}$$

$v_g = gas\ terminal\ velocity\ \left({}^{ft}/_{sec}\right)$

$d_g = gas\ bubble\ diameter\ (in)$

$\rho_l = liquid\ density\ \left({}^{lb}/_{ft^3}\right)$

$\rho_g = gas\ density\ \left({}^{lb}/_{ft^3}\right)$

$\mu_l = liquid\ viscosity\ (in)$

The gas capacity equation is used to determine the gas a given separator dimension can process using Newton's Law for laminar flow as a limiting case. Equation 1 is the fundamental Stokes Law equation in English units. This law states that, left to its own devices, a gas bubble of a certain diameter would rise through a continuum of liquid at a certain velocity. Vg is terminal rising velocity for gas.

The gas velocity calculated in Equation 1 is also an in-situ value that is related to the gas flow rate measured at standard conditions. The terminal gas velocity calculated in Equation 2 is the actual velocity of a gas bubble in the separator, which is dependent on the physical size of the vessel and the flowrate of gas going through it.

$$v_g = \frac{q_{qsc} * z * T * 14.73}{A_g * p * 520 * (86{,}400)} \tag{2}$$

$v_g = gas\ terminal\ velocity\ \left({}^{ft}/_{sec}\right)$

$q_{qsc} = gas\ flow\ rate\ at\ standard\ conditions\ \left({}^{scf}/_{day}\right)$

$A_g = cross\ sectional\ flow\ area\ of\ the\ separator\ (ft^2)$

$p = pressure\ (psia)$

$T = temperature\ (R)$

$z = compressibility\ factor$

It is desired to have the actual gas in the separator behave according to Stokes law. Setting Equation 1 equal to Equation 2 and solving for Ag, the flow area needed to process just the gas is determined (simultaneously as the gas behaves like bubbles in the liquid as defined by Stokes Law) in Equation 3. In this way, the separator is being designed so that gas is bubbling through the liquid in the middle tube, not churning or erupting.

$$A_g = 1.8 * 10^{-8} * \frac{q_{qsc} * z * T * \mu_l}{p * {d_g}^2 * (\rho_l - \rho_g)} \tag{3}$$

Liquid Capacity Equation:

The flowrate of the liquid we intend to process is a function of the cross-sectional flow area of the liquid needed to handle just the liquid, shown in Equation 4.

$$q_l = \frac{A_l * L * 86{,}400}{t * 5.615} \tag{4}$$

$q_l = liquid\ flow\ rate\ \left({}^{bbl}/_{day}\right)$

$A_l = cross\ sectional\ flow\ area\ of\ the\ separator\ for\ the\ liquid\ ft^2$

$L = length\ of\ middle\ tube\ (ft)$

$t = fluid\ retension\ time\ (sec)$

Retention time “t” is determined from the actual liquid and gas rates divided by the actual separator volume using Equation 5, below:

$$t = \frac{V_{sep}}{5.615\, q_l + q_g} * 86{,}400 \tag{5}$$

$$t = fluid\ retension\ time\ (sec)$$
$$V_{sep} = actual\ volume\ inside\ separator\ (ft^3)$$
$$q_g = in - situ\ gas\ rate\ \left({ft^3}/{day} \right)$$

The in-situ gas rate is related to the measurable gas flow rate at standard conditions through Equation 6.

$$q_g = q_{qsc} \frac{z * T * 14.7}{p * 520} \tag{6}$$

Rearranging Equation 4 for Al is shown in Equation 7, which is the separator area needed to process just the liquid.

$$A_l = 6.5 * 10^{-5} * \frac{q_l * t}{L} \tag{7}$$

Finally, to determine the TOTAL area required to process the gas and liquid simultaneously (As shown in Table 2), Equation 3 is added to Equation 7. The summation of these equations is under the assumption that, if the separator has a big enough area (Ag + Al), then the separator will work.

Allowed Gas-Liquid Ratio (TEST 1):

$$\boxed{GLR = \frac{\left(A - 6.5 * 10^{-5} * \frac{q_l t}{L}\right) p{d_g}^2 * \left(\rho_l - \rho_g\right)}{1.8 * 10^{-8} * q_l zT\mu_l}} \quad (8)$$

$$GLR = allowable\ gas - liquid\ ratio$$

$$A = total\ flow\ area\ for\ a\ given\ separator\ (ft^2)$$

$$q_l = liquid\ flow\ rate\ \left({}^{bbl}/_{day}\right)$$

$$t = fluid\ retension\ time\ inside\ the\ separator\ (sec)$$

$$L = length\ of\ middle\ tube\ (ft)$$

$$p = pressure\ (psia)$$

$$z = compressibility\ factor$$

$$T = temp\ (R)$$

Allowed Gas-Liquid Ratio is obtained by adding Equation 3 to Equation 7 to obtain the total flow area for both the gas and the liquid, and then rearranging. The result is shown as Equation 8, which is in English units. The flow area in Equation 8 is the actual flow area available for any given separator, with examples shown in Table 2, p.11.

The GLR of a well on production can be compared to the *Allowable GLR* of the separator, which is dependent on separator dimensions and properties of fluid flowing through it. If the production from the well's GLR exceeds the allowable GLR from the separator, then the separator in question is not adequate to separate gas from the liquid – *this is the first function test of the separator design*. If the actual GLR is larger than the allowable GLR, we expect large gas bubbles (greater than dg) to frequently pass down the middle tube, and potentially into the rod lift pump. If the actual GLR is less than the allowable GLR, we do not expect to see any bubbles larger than dg. This function test can be used to determine if a separator has the dimensions necessary for adequate separation.

Liquid Velocity Down Middle Tube (TEST 2):

$$\boxed{V_{in} = \frac{q_l * 5.615 * (1728)}{A_{in} * 86{,}400}} \quad (9)$$

$V_{in} = liquid\ velocity\ into\ the\ pump\ intake\ (down\ middle\ tube)\ \left({}^{in}/_{sec}\right)$

$q_l = liquid\ flow\ rate\ \left({}^{bbl}/_{day}\right)$

$A_{in} = pump\ intake\ cross\ sectional\ flow\ area\ (in^2)$

$A_{in} = \pi * \left(\left(\frac{ID}{2}\right)^2 - \left(\frac{OD}{2}\right)^2\right)$

$ID = internal\ diameter\ of\ middle\ tube\ (in)$

$OD = outer\ diameter\ of\ tubing\ (in)$

Gas Bubble Diameter is a variable that must be set. The smaller the gas bubble, the slower it rises through the liquid. Based on experiments, a generally accepted bubble diameter that is allowed into the rod lift pump (because not all the gas can be separated) is 0.25 inches. This means that bubbles of this diameter or larger will be separated. From these experiments, a fluid velocity (down middle tube) of 6 in/sec is the accepted maximum above which gas bubbles larger than 0.25 in. will be carried into the pump. This general rule is a function of liquid viscosity. (Bommer and Podio, 2015).

If the velocity down the middle tube is calculated to be less than or equal to 6 in/sec, only gas bubbles smaller than 0.25” will be drawn into the pump. If larger, then we can expect the pump to take in bubbles larger than 0.25 in – *this is the second function test of the separator design.*

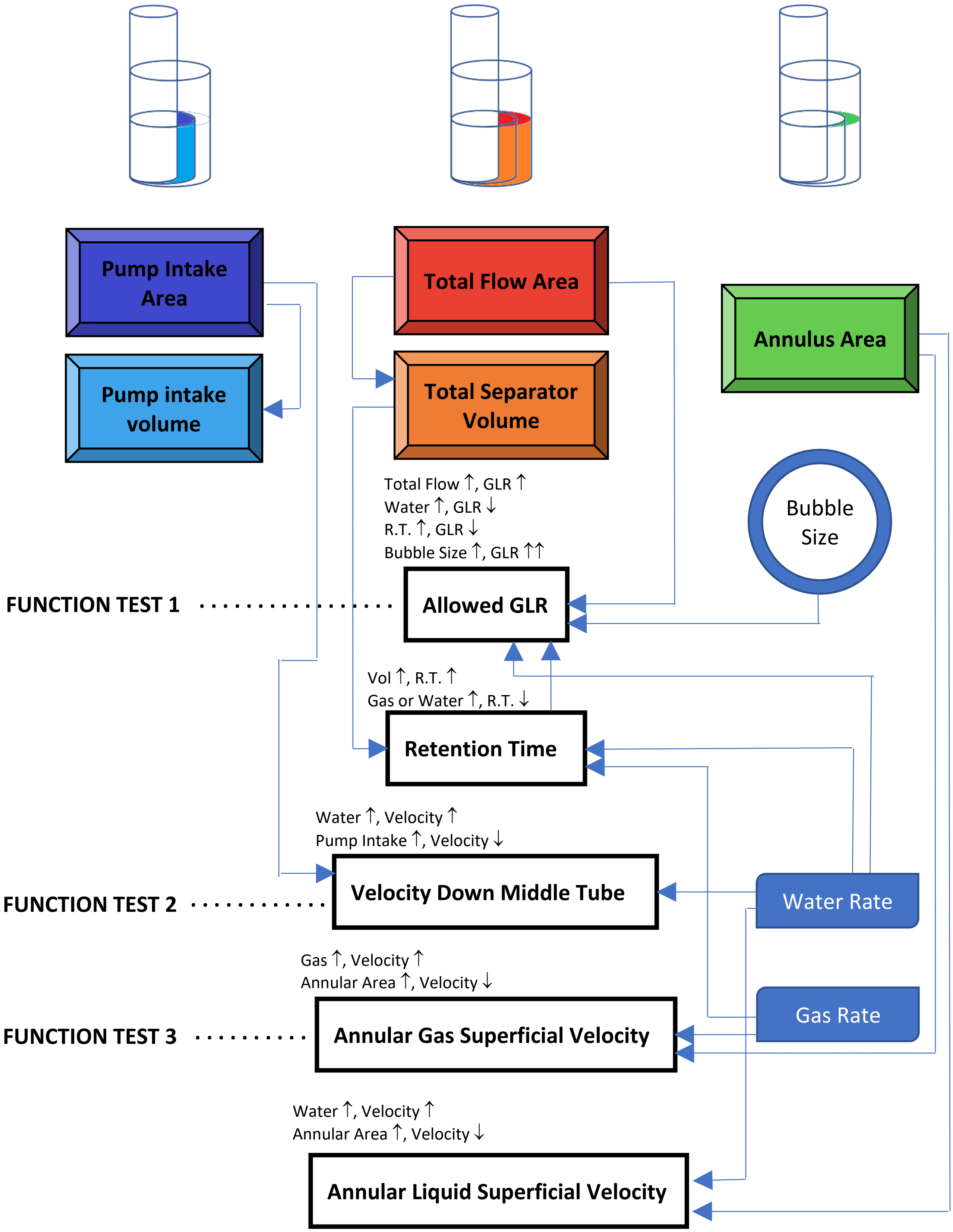
Gas – Liquid Annular Flow Regime (TEST 3):

The flow pattern between the liquid and the gas that is established in the annulus between the middle and outer tubes of the separator will affect the way in which the separator functions. If the flow regime is one of gas bubbles in the liquid, then Stokes Law is satisfied as described in Test 1 and the separator will function. If the flow pattern becomes more chaotic it is probable that some of the gas will form into slugs or even boil or churn to the point where the gas may be impossible to keep out of the middle tube space. There are two possibilities that have been hypothesized. The first considers flow in a pipe (see the flow map in Bommer and Podio, 2015) in which bubble flow is surpassed when the superficial gas velocity in the pipe exceeds 10 ft/sec. The superficial gas velocity is defined as the gas velocity if only gas is flowing through the pipe. The second considers flow in an annulus (Hernandez, 2011) where bubble flow surpassed at a superficial gas velocity of only 0.32 ft/sec. Depending on which limit one chooses will greatly affect the design of the separator – *this is the third function test of the separator design.* These choices will be tested and discussed in the results section.

Relationship Flowchart

Shown on page 34 is a Relationship Flowchart of how each separator dimension impacts the variables used to design the separator. This flowchart can be used to modify or build a new separator for a well. For example, if a well is expected to have a very high liquid rate, the flowchart indicates that this rate will result in a higher velocity of liquid down the middle tube and a higher annular liquid superficial velocity. For adequate separation, a lower liquid velocity down the middle tube may be required, dependent on the chosen bubble size to be separated. Following the flowchart's relationship guide, it is seen that the pump intake area also affects liquid velocity down the middle tube. To offset the increase caused by a high liquid rate well, increasing the pump intake area can reduce the liquid velocity down the middle tube to the desired amount. The zone highlighted in dark blue on the pump image represents the pump intake area. This pump image can be interpreted visually to conclude that the only way to increase the pump intake area is to reduce the diameter of the inner tube (production tubing), or to increase the diameter of the middle tube. In this way, any new design considerations can be pursued with the guidance of the flowchart created below.

It is hypothesized that if a separator passes all 3 function tests identified previously, then the separator will successfully separate the desired gas bubbles out of the liquid.


Pump Intake Area
Pump intake volume
Total Flow Area
Total Separator Volume
Annulus Area
Total Flow ↑, GLR ↑
Water ↑, GLR ↓
R.T. ↑, GLR ↓
Bubble Size ↑, GLR ↑↑
Bubble Size
FUNCTION TEST 1
Allowed GLR
Vol ↑, R.T. ↑
Gas or Water ↑, R.T. ↓
Retention Time
Water ↑, Velocity ↑
Pump Intake ↑, Velocity ↓
FUNCTION TEST 2
Velocity Down Middle Tube
Water Rate
Gas ↑, Velocity ↑
Annular Area ↑, Velocity ↓
FUNCTION TEST 3
Annular Gas Superficial Velocity
Gas Rate
Water ↑, Velocity ↑
Annular Area ↑, Velocity ↓
Annular Liquid Superficial Velocity

SECTION 4: RESULTS AND DISCUSSIONS

Large Separator Tests

The following tests presented in Table 5 were initially completed using the large separator. The first 4 columns are the air and water rate combinations pumped into the separator. Columns 6 (actual GLR present) and 7 (allowable GLR as per separator dimensions) indicate that the allowable GLR for the separator far exceeds the actual GLR present – Function Test 1 is passed for all tests. Experiment 7 has a liquid velocity down the middle tube noticeably higher than 6 in/sec – Function Test 2 is failed for experiment 7. In theory, as the plunger is in motion in the constructed separator, bubbles LARGER than 0.25 inches (depending on how much higher above 6 in/sec the experiment falls) should be seen being lifted to surface for experiment 7. However, the bubbles actually observed were roughly 0.25 inches in diameter (Figure 5). Although experiment 7 failed Function Test 2, we observed bubbles no larger than 0.25 inches in diameter, so the separator was successful in separation (Figure 18). This can be explained by the dependence of bubble separation on liquid viscosity. The liquid used in these tests is water and the actual maximum liquid velocity for water is 9.5 ft/sec. (Figure 16). The 6 in/sec. value is used as a more general velocity threshold for downhole gas separators that process more viscous fluids.

In summary, all the gas/liquid combinations tested in Table 5 had adequate separation, with bubbles no larger than 0.25 inches present inside the pump. Experiment 7 was the only one to have failed any one of the function tests, but this failure could have been attributed to the more general use of the 6 in/sec. velocity threshold.

Table 5 – Large Separator Experimental Results

Experiment	Air Rate L/min	cuft/day	Water Rate gpm	BPD	GLR cuft/bbl	Allowed GLR cuft/bbl	Retension Time sec	Liquid Velocity Middle Tube in/sec	Annular Gas Superficial Velocity ft/sec
1	16	813.65	4.39	150.51	5.41	1,826.94	19.32	3.07	0.17
2	21	1,067.92	4.39	150.51	7.10	2,079.25	16.75	3.07	0.23
3	30	1,525.59	4.37	149.83	10.18	2,411.91	13.54	3.06	0.32
4	48	2,440.95	4.37	149.83	16.29	2,782.94	9.76	3.06	0.52
5	197	10,018.06	4.37	149.83	66.86	3,452.35	2.95	3.06	2.13
6	457	23,239.87	4.41	151.20	153.70	3,577.66	1.33	3.09	4.93
7	465	23,646.69	10.22	350.40	67.48	1,477.26	1.25	7.16	5.02
8	520	26,443.61	8.7	298.29	88.65	1,767.78	1.14	6.09	5.61
9	12	610.24	8.73	299.31	2.04	498.76	13.99	6.11	0.13

Figure 18 - Bubbles no larger than 0.25 inches inside pump

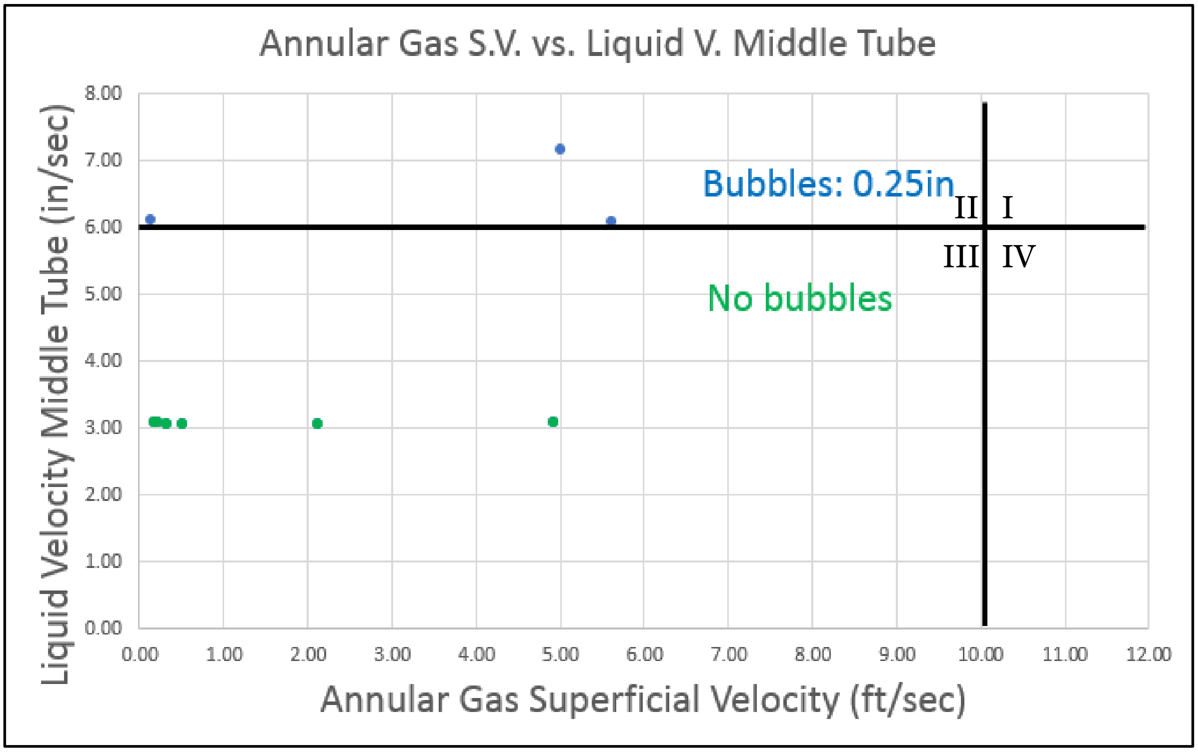


Figure 19 - Large Separator Results - Middle Tube Velocity v. Gas superficial Velocity

🔵 Bubbles no larger than 0.25 inches present 🟢 No bubbles present 🔴 Bubbles of diameter 0.5 inches present

Figure 19 is a chart used to summarize all the experiments done in Table 5. On the Y-axis is liquid velocity down the middle tube (Function Test 2) and the X-axis was chosen to be annular gas superficial velocity (Function Test 3), which describes the gas flow in the annulus between the outside tube and middle tube. Figure 19 contains Function Test 2 on the y-axis and Function Test 3 on the x-axis.

A horizontal line is displayed across the generic choice for liquid velocity of 6 in/sec, marking the boundary above which Function Test 2 is failed and bubbles larger than 0.25 inches could be seen entering the pump, depending on the viscosity of the liquid. A vertical line is displayed on 10 ft/sec, marking the boundary above which we hypothesize Function Test 3 is failed, assuming the limit for pipe flow, not annular flow, is used.

It is relevant to note that the Hernandez et al paper on **annular** flow regimes showed 0.32 ft/sec as an annular gas velocity above which churn flow exists in annular flow settings. Even though Function Test 3 is representing annular flow, the separator tests conducted in Table 5 continued to effectively separate gas and water with annular gas velocities up to 5.61 ft/sec. This was the highest annular gas velocity tested, and it is possible that even higher velocities could have resulted in successful gas separation. Hernandez's estimation of 0.32 ft/sec annular gas velocity was likely too restrictive to be described as churn flow, as the experiment results here showed no problem in separating annular gas velocities higher than 0.32 ft/sec.

These boundary lines make up the four quadrants in the chart shown in Figure 19. Quadrant 2 contains blue points (representing Experiment 7, 8, 10) indicating that bubbles of roughly 0.25 inch diameter were observed in the pump on the upstroke. Quadrant 3 shows green bubbles (representing the remaining experiments) indicating no bubbles were observed inside the pump during the pumping process.

Large Separator Tests – Round 2

It was important to determine the failure criteria on the large separator, so a second round of testing was proposed. Ideally, observing the bubbles inside the pump using high gas rates between 1200 – 1400 L/min, tested with high water rates between 13 – 18 gal/min, would accurately conclude whether the failure criteria is 6 in/sec and 10 ft/sec on the y and x axis, respectively. If tested, these air/water combinations would result in data points further away from the origin in Quadrant 1 of the Liquid Velocity vs. Gas Velocity graphs.

520 Liters/min was the maximum output of the air compressor, and 10.4 gal/min was the maximum water rate available. Due to the limitations of the compressor and water source, high air and water rates were not able to be tested. Table 6, columns 2 and 4 show the air and water rates pumped in round 2 for observation.

Table 6 – Large Separator Results – Round 2

Experiment	Air Rate L/min	cuft/day	Water Rate gpm	BPD	GLR cuft/bbl	Allowed GLR cuft/bbl	Retension Time sec	Liquid Velocity Middle Tube in/sec	Annular Gas Superficial Velocity ft/sec
1	512	26,036.79	10.4	356.57	73.02	1,460.19	1.14	7.28	5.53
2	411	20,900.62	10.4	356.57	58.62	1,435.01	1.40	7.28	4.44
3	400	20,341.24	8.5	291.43	69.80	1,780.72	1.46	5.95	4.32
4	400	20,341.24	6.25	214.29	94.93	2,470.48	1.49	4.38	4.32

Figure 20 shows the 4 quadrant chart with the added Round 2 experiments, labeled below.

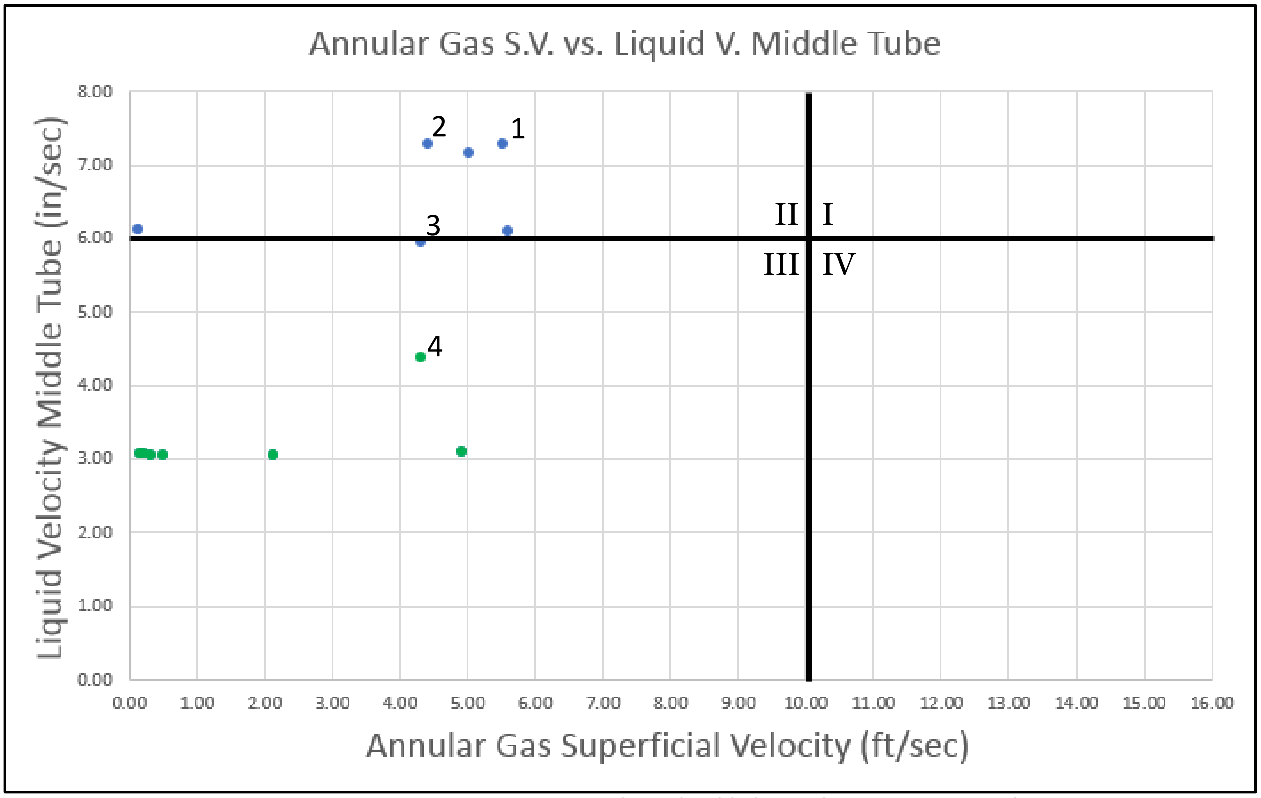


Figure 20 - Large Separator Results with Added Round 2 Experiment Results

🔵 Bubbles no larger than 0.25 inches present 🟢 No bubbles present 🔴 Bubbles of diameter 0.5 inches present

In total, 0.25 inch bubbles were seen when the liquid velocity was above 6 in/second. No bubbles were present in Experiment 4. In all the cases, the large separator successfully separated out bubbles larger than 0.25 inches.

Large Separator Tests – Angled 20° and 10°

The large separator was also tested at an angle of 20 degrees and 10 degrees (Table 7 and 8 respectively) to determine if the slanted posting (Figure 22) helps in separation – relevant for separators positioned in deviated wells. Similar rates were pumped as the previous vertical experiment. Figure 21 shows that even though some experiments exceeded the 6 in/sec, no bubbles were observed inside the pump. This indicates that the angled placement of the separator assisted further in gas separation.

Table 7 - Large Separator Angled 20 degrees – Experimental Tests

Experiment	Air Rate L/min	cuft/day	Water Rate gpm	BPD	GLR cuft/bbl	Allowed GLR cuft/bbl	Retension Time sec	Liquid Velocity Middle Tube in/sec	Annular Gas Superficial Velocity ft/sec
1	17	864.50	4.41	151.20	5.72	1,870.65	18.70	3.09	0.18
2	21	1,067.92	4.41	151.20	7.06	2,065.66	16.72	3.09	0.23
3	29	1,474.74	4.41	151.20	9.75	2,353.26	13.79	3.09	0.31
4	48	2,440.95	4.41	151.20	16.14	2,751.24	9.74	3.09	0.52
5	197	10,018.06	4.41	151.20	66.26	3,418.61	2.95	3.09	2.13
6	457	23,239.87	4.41	151.20	153.70	3,577.66	1.33	3.09	4.93
7	460	23,392.43	10.28	352.46	66.37	1,466.74	1.26	7.20	4.96
8	518	26,341.91	8.71	298.63	88.21	1,765.22	1.14	6.10	5.59
9	19	966.21	8.69	297.94	3.24	688.77	12.14	6.09	0.21

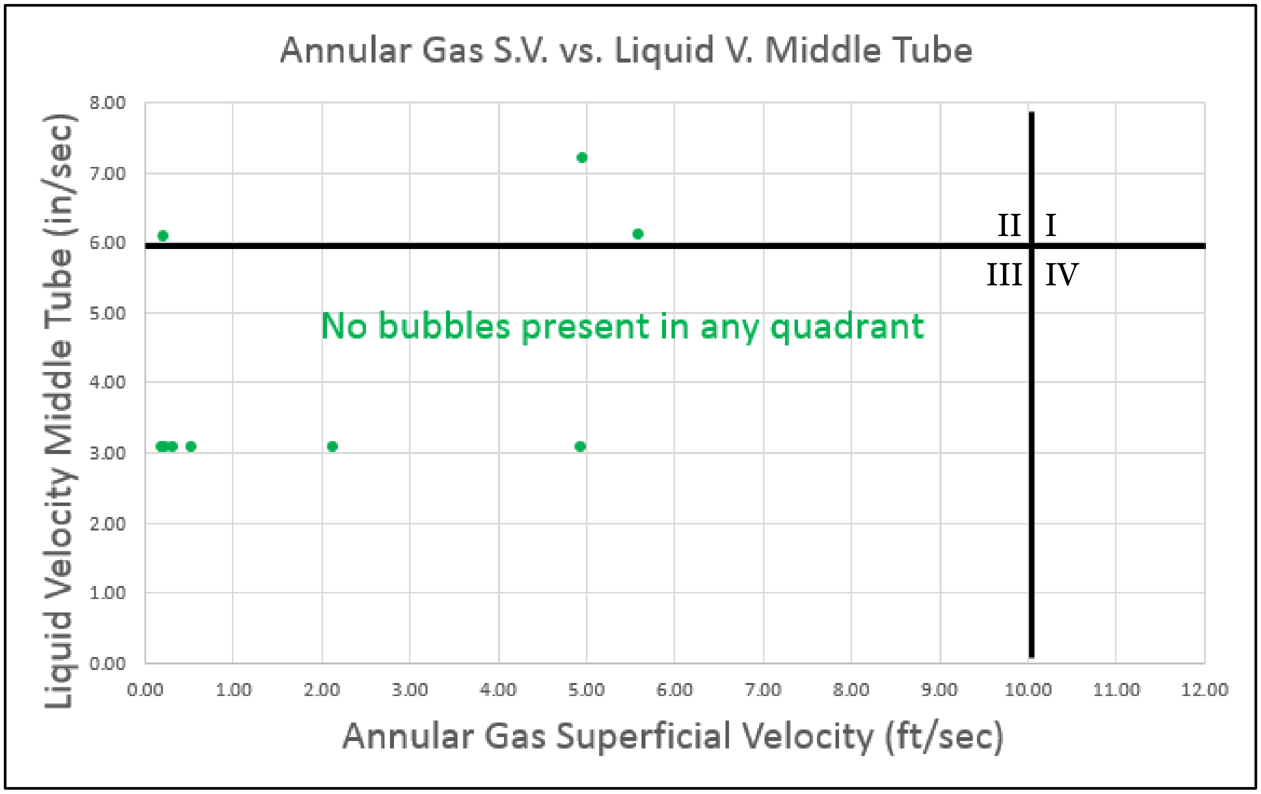


Figure 21 - Large Separator Angled 20 degrees – Experimental Results

🔵 Bubbles no larger than 0.25 inches present 🟢 No bubbles present 🔴 Bubbles of diameter 0.5 inches present

Figure 22 - Angled Separator

Similar tests were repeated by slanting the separator at 10 degrees, and are shown in Table 8. No bubbles in the pump were observed again (Figure 23). The angled separator allows gravity to assist in the separation process. This suggests that attempting to place the separator in a slightly deviated part of the well could further help with separating gas from liquid in high gas wells.

Table 8 - Large Separator angled 10 degrees – Experimental Tests

								Liquid Velocity	Annular Gas
	Air Rate		Water Rate		GLR	Allowed GLR	Retension Time	Middle Tube	Superficial Velocity
Experiment	L/min	cuft/day	gpm	BPD	cuft/bbl	cuft/bbl	sec	in/sec	ft/sec
1	14	711.94	4.41	151.20	4.71	1,691.04	20.53	3.09	0.15
2	20	1,017.06	4.41	151.20	6.73	2,020.90	17.17	3.09	0.22
3	30	1,525.59	4.41	151.20	10.09	2,382.28	13.49	3.09	0.32
4	49	2,491.80	4.41	151.20	16.48	2,765.81	9.59	3.09	0.53
5	189	9,611.24	4.41	151.20	63.57	3,407.34	3.06	3.09	2.04
6	460	23,392.43	4.41	151.20	154.71	3,578.48	1.32	3.09	4.96
7	499	25,375.70	10.27	352.11	72.07	1,477.28	1.17	7.19	5.39
8	518	26,341.91	8.71	298.63	88.21	1,765.22	1.14	6.10	5.59
9	12	610.24	8.75	300.00	2.03	496.78	13.96	6.13	0.13

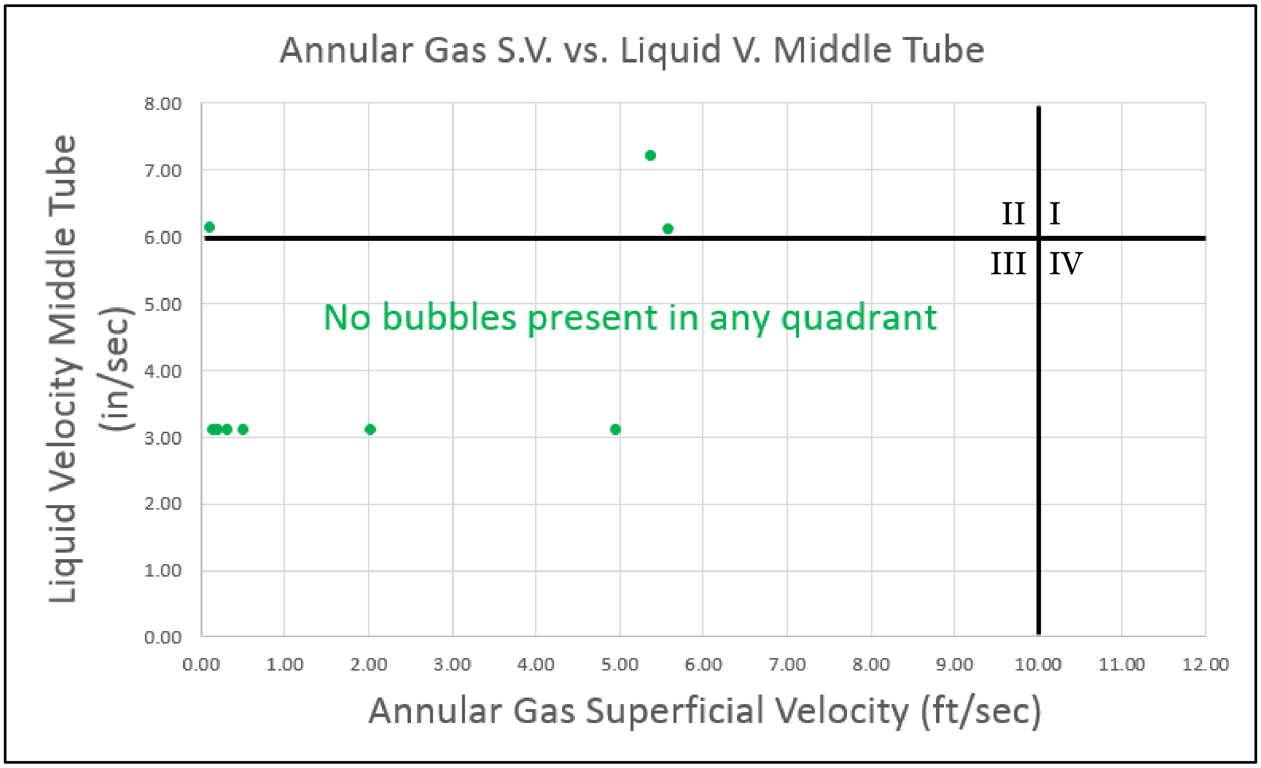


Figure 23 - Large Separator Angled 10 degrees – Experimental Results

🔵 Bubbles no larger than 0.25 inches present 🟢 No bubbles present 🔴 Bubbles of diameter 0.5 inches present

Small Separator Tests

The smaller separator was first tested using the air and water rates presented in Table 9. When the experiments significantly exceeded the 6 in/sec middle tube velocity marker AND the 10 ft/sec annular gas superficial velocity marker (Function Tests 2 and 3, respectively), the bubbles observed were closer to 0.5 inches in diameter and larger – these experiments are shown in red in Quadrant 1 of Figure 24. The red points correspond to Experiment 3 and 4 in which the separator has failed to adequately separate liquid from gas by letting 0.5 inch bubbles into the pump (Figure 25). The remaining experiments are seen in Quadrants 2, 3, and 4, all with 0.25 inch bubbles or no bubbles observed – in these quadrants the separator was successful in separation.

Table 9 - Small Separator – Experimental Results

Experiment	Air Rate L/min	cuft/day	Water Rate gpm	BPD	GLR cuft/bbl	Allowed GLR cuft/bbl	Retension Time sec	Liquid Velocity Middle Tube in/sec	Annular Gas Superficial Velocity ft/sec
1	16	813.65	1.75	60.00	13.56	795.66	2.51	14.08	1.20
2	100	5,085.31	1.81	62.06	81.95	1,018.12	0.53	14.56	7.51
3	300	15,255.93	1.81	62.06	245.84	1,063.60	0.19	14.56	22.52
4	400	20,341.24	1.83	62.74	324.20	1,057.68	0.14	14.72	30.03
5	400	20,341.24	0.44	15.09	1,348.38	4,456.64	0.14	3.54	30.03
6	300	15,255.93	0.38	13.03	1,170.96	5,157.08	0.19	3.06	22.52
7	100	5,085.31	0.32	10.97	463.51	6,079.74	0.56	2.57	7.51
8	30	1,525.59	0.38	13.03	117.10	4,944.66	1.81	3.06	2.25
9	0	0.00	0.25	8.57	0.00	-1.40	60.12	2.01	0.00
10	50	2,542.66	0.25	8.57	296.64	7,730.02	1.12	2.01	3.75
11	12	610.24	0.25	8.57	71.19	7,300.47	4.40	2.01	0.90

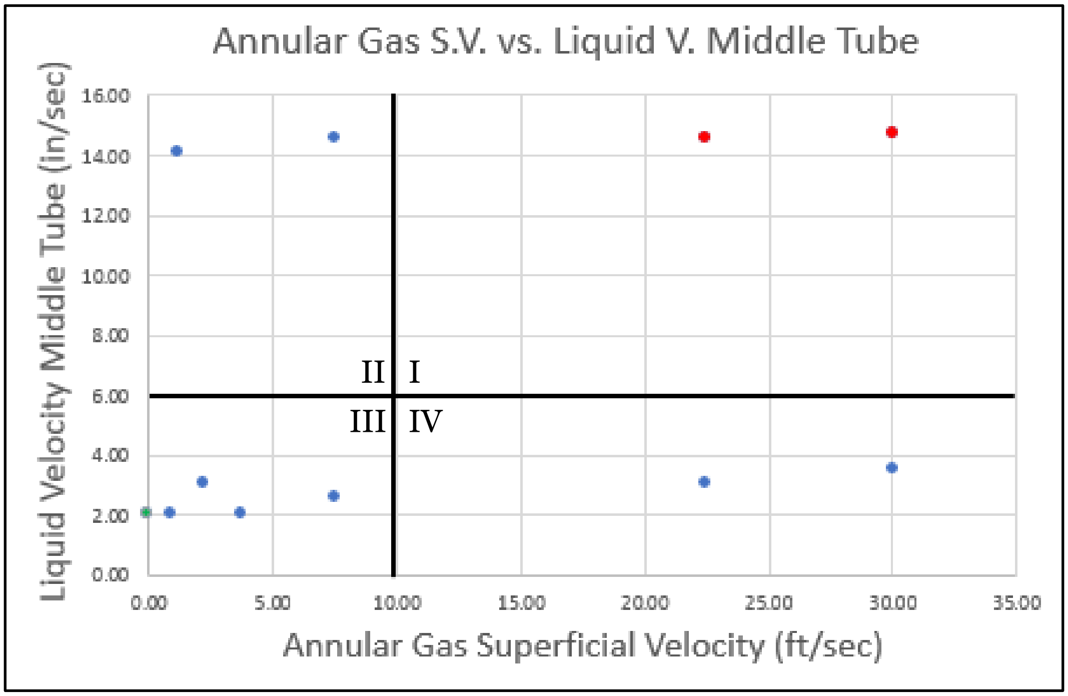


Figure 24 - Small Separator Results

🔵 Bubbles no larger than 0.25 inches present 🟢 No bubbles present 🔴 Bubbles of diameter 0.5 inches present

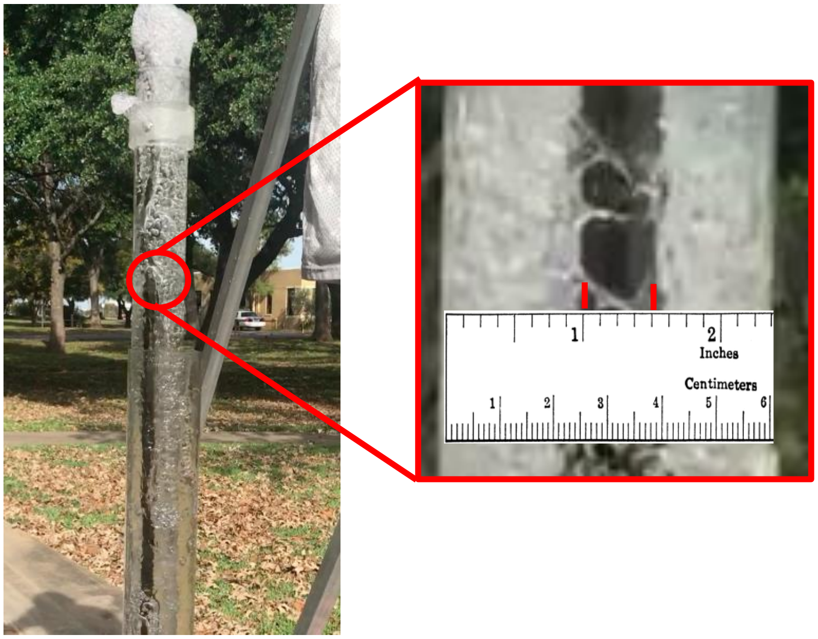


Figure 25 - Bubbles of 0.5 inches visible inside the pump (Exp. 3 and 4)

Small Separator Tests – Round 2

The small separator failing had already been observed in the initial testing. To more definitively determine the criteria which caused the small separator to fail, more tests were conducted with liquid and air rates that resulted in a high liquid velocity down the middle (above 6 in/sec) and a high annular gas superficial velocity (above 10 ft/sec) for the small separator. These water/air rates resulting in Quadrant 1 will be smaller than those for the larger separator because the pump intake area and annular area are smaller for the small separator (refer Relationship Flowchart). These new tests are presented below in Table 10.

Table 10 - Small Separator Tests - Round 2

								Liquid Velocity	Annular Gas
	Air Rate		Water Rate		GLR	Allowed GLR	Retension Time	Middle Tube	Superficial Velocity
Experiment	L/min	cuft/day	gpm	BPD	cuft/bbl	cuft/bbl	sec	in/sec	ft/sec
1	210	10,679.15	1.2	41.14	259.56	1,606.16	0.27	9.65	15.77
2	150	7,627.97	1.24	42.51	179.42	1,539.78	0.37	9.98	11.26
3	302	15,357.64	1.22	41.83	367.16	1,589.69	0.19	9.82	22.67
4	247	12,560.72	1.28	43.89	286.21	1,508.75	0.23	10.30	18.54
5	146	7,424.55	1.58	54.17	137.06	1,197.20	0.37	12.71	10.96
6	215	10,933.42	1.58	54.17	201.83	1,212.52	0.26	12.71	16.14

The tests conducted in Table 10 all failed Function Test 2 and 3 (liquid velocity and gas velocity, respectively). The goal of running these experiments was to determine whether the separator separated gas bubbles larger than 0.25 inches from entering the pump. The images inside the pump for each experiment are presented below:

Experiment 3 – 0.5 inches *Experiment 2 – 0.5 inches* *Experiment 1 - 0.75 inches*

Experiment 6 – 0.75 inches *Experiment 5 – 0.5 inches* *Experiment 4 – 0.5 inches*

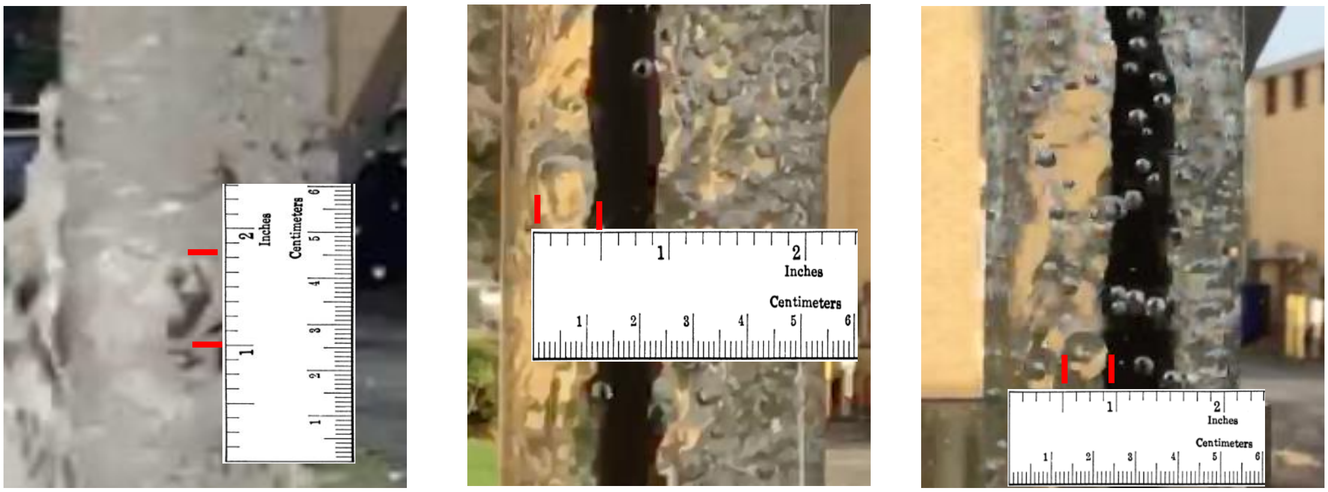


Figure 26 - Experiments 1 - 6 images for Round 2 on Small Separator

For all of the experiments in Table 10, bubbles larger than 0.25 inches were present inside the pump – these tests failed to separate bubbles larger than 0.5 inches. Due to the compressor limitations, the allowable GLR was never exceeded, so Function Test 1 (allowable GLR for the separator) was always passed for all the experiments. The results from this experiment suggest that, if a liquid/gas rate combination fails to pass two out of the three function tests, then the separator will not adequately separate gas from liquid. Shown below in Figure 27 are the added new experiments, labeled one through six, to show all the experiments run on the small separator.

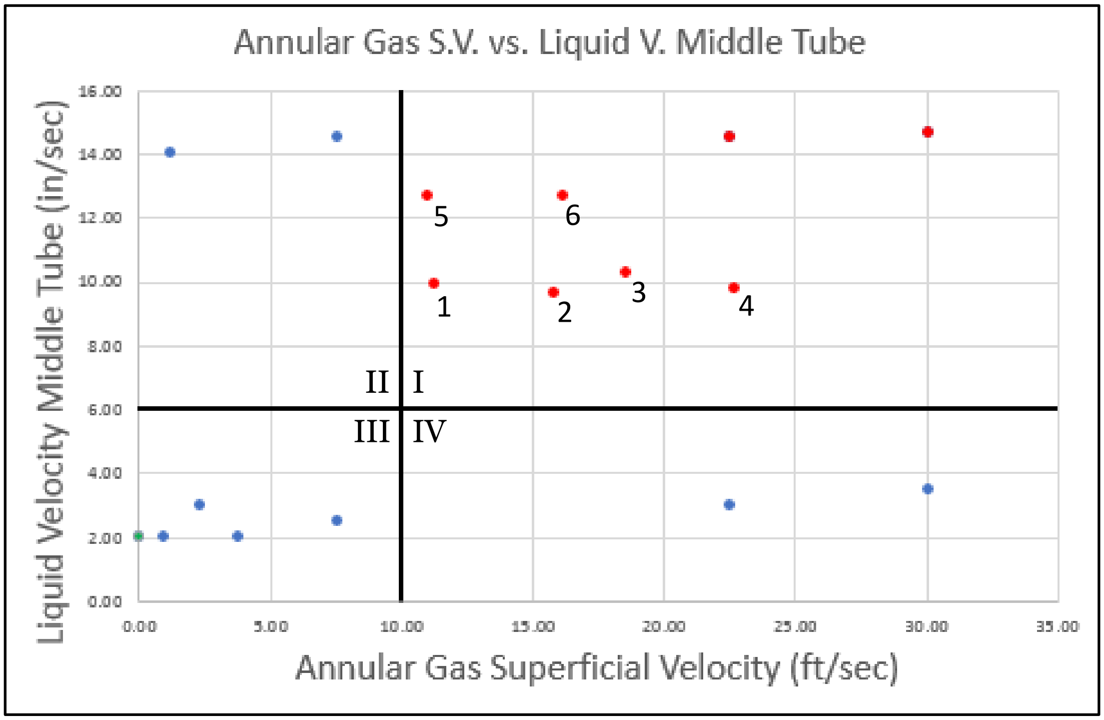


Figure 27 - Small Separator Results with added Round 2 Results

🔵 Bubbles no larger than 0.25 inches present 🟢 No bubbles present 🔴 Bubbles of diameter 0.5 inches present

Experiments 3 and 4 showed bubble sizes as large as 0.75 inches, the largest found in all the experiments. Interestingly, these two experiments among the six newly conducted had the two highest annular gas superficial velocity. This initial observation suggested a trend may exist between the observed bubble size and annular gas superficial velocity: in Quadrant 1, larger bubble sizes could be observed with increasing annular gas superficial velocities. The videos and pictures for all the tests, including the two previously run for Quadrant 1, were analyzed to see if any correlation existed between bubble size and annular gas velocity. The evidence did not conclude any such trends existed.

In summary, all tests landing in Quadrant 1 for the small separator failed to separate the gas adequately, and allowed bubbles larger than 0.25 inches inside the pump.

SECTION 5 – CONCLUSIONS AND FUTURE RESEARCH

Overview:

In this study, we address two broad, interconnected problems on artificially lifted horizontal wells: 1) Having gas inside the beam pump 2) Having an insufficient discharge pressure from ESPs/hydraulic pumps to lift fluid to the surface. A proposed solution is to use a gravity based down-hole gas-liquid separator which also plays the role of a pump connector between a beam pump and an ESP/hydraulic pump. A model of this separator/connector was constructed for analysis.

This separator/connector's effectiveness to separate gas bubbles above a specific size (0.25 inches) was tested with various air/water rates. If the separator allowed bubbles larger than 0.25 inches inside the pump, then it has failed. The objective from experimenting was to propose a general failure criteria for the constructed separator, which could be extended to separators of any size and dimension.

Three functions tests (i.e. variables) calculated on the separator were recommended to be used to quantify the failure criteria:

1) Allowable Gas-Liquid Ratio the separator will process
2) Liquid Velocity falling down the middle tube of the separator
3) Annular Gas Superficial Velocity between outside and middle tube

- If the dimensions of the separator result in a higher Allowable Gas-Liquid Ratio than the actual GLR in the device, then Test 1 is passed.
- If the Liquid Velocity down the middle tube is less than 6 in/sec, then Test 2 is passed.
- If the Gas Velocity in the annulus is less than 10 ft/sec, then Test 3 is passed.

Conclusions:

It was initially hypothesized that if any separator passed all three function tests for a given air/water rate, then it would successfully separate bubbles larger than 0.25 inches. Based on the resulting evidence from testing a large and small separator, the hypothesis proved true. All experiments, conducted on the large and small separator, effectively separated gas bubbles larger than 0.25 inches when the three function tests were passed.

Additionally, for both separators, failing Function Test 2 alone (Quadrant 2) also meant successful separation but the large separator should have been tested with a higher liquid velocity down the middle tube for a more accurate conclusion. Failing Function Test 3 alone (Quadrant 4) proved successful for the small separator, but was never tested with the large separator.

Most importantly, the smaller separator results showed that failing Function Test 2 and 3 (Quadrant 1) meant the separator would fail to effectively separate the gas. But this evidence was not enough to generally conclude that failing ANY 2 of the 3 tests would inhibit the separator from functioning. Due to inadequate compression available from the compressor, Function Test 1 (Allowable GLR > actual GLR) was never observed under failure. It is possible that Function Test 1 is independent of the other two, such that if Function Test 1 fails, then the separator will not function regardless of passing Function Test 2 and 3.

Future Research:

To continue this research, the large separator needs to be tested and observed under high enough air/water rates such that the results are deep in Quadrant 1, further away from the origin. Below in Figure 28 is a proposal of future experiments in black, shown with the existing results on the large separator.

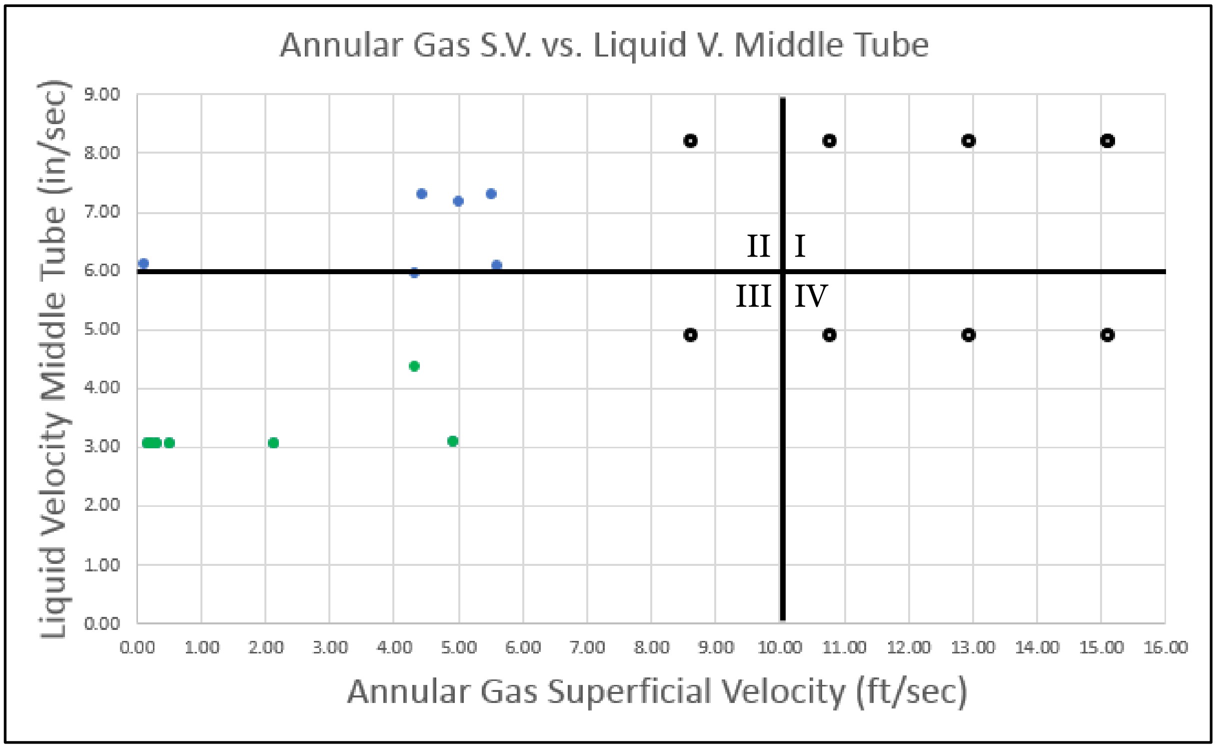


Figure 28 - Large Separator Results with Future Experiment proposal

🔵 Bubbles of diameter 0.25 inches present 🟢 No bubbles present 🔴 Bubbles of diameter 0.5 inches present

⭘ Future Experiment Results – Unknown bubble size presence

From the experiments done on the large separator, we found evidence that operating the separator/connector at an angle (20ᶿ and 10ᶿ) helped take out ALL the bubbles present inside the pump. Future experiments on the small and large separator need to determine what the optimal angle of operation is, with consideration for feasibility in the field. An angled separator assists in separation, so this will likely change the thresholds of 6 in/sec liquid velocity and 10 ft/sec gas velocity. Determining the failure criteria for the large and small separators operating at an angle can increase the clarity on the separator usage in deviated wells.

SECTION 6 – REFERENCES

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