RISER GAS MIGRATION IN EC-DRILL™ OPERATIONS

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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December 2015

Major Subject: Petroleum Engineering

ABSTRACT

Increased demand for oil and gas pushes producers to develop and enhance methods for exploring deeper reservoirs located in offshore fields. With greater depths comes greater complications, this greater water depth along with other unknown formation factors in conjunction with the high daily rental cost of offshore rigs, equipment and personnel renders performing research and development on a deep water offshore well prohibitively expensive. However, with the occurrence of incidents such as the Macondo in 2010, regulators and operators have been prompted to be more cautious and perform research in offshore drilling operations, to better understand the unknown factors which involve the deepwater conditions.

This thesis investigates riser gas migration while drilling offshore wells using the EC-Drill™ technology. EC-Drill™ is a variation of Dual Gradient Drilling, where two fluid gradients are achieved by controlling the annular mud level in the riser via subsea pumps, voiding the top section to air, forming the two gradients; air in top section and drilling mud for the remaining fluid column, providing dynamic control of the Bottom Hole Pressure and improved drilling and well control capabilities, which reduce costs, non-productive time and create a safer drilling environment. However, one of the issues of voiding the riser to air in the EC-Drill™ is that if a gas kick occurs or gas is drilled, then the gas entering the system will rise to the voided section of the riser creating a combustible mixture of gas and air below the rig floor, leading to devastating results such as equipment damage, losing the

well, and even death. These results make it important to understand and mitigate the problem of gas migration. This study provides the design process of the experiment facility in which the gas migration study was performed and the preliminary tests that were done to study gas migration.

The method of elimination that was proposed for the testing facility was called the “top fill technique”, where additional drilling fluid is injected from the top of the riser in the annulus, causing a downward flow motion which is meant to prevent the gas from rising up. The injected drilling fluid is then returned to the rig floor through the EC-Pump mounted on the riser along with the gas. This method requires *a priori* knowledge of the amount of drilled gas, mud properties, circulation rates, the injection rate and the required downward flow which is obtained through experiments.

To perform the necessary experiments a small-scale simulator was designed at the University Services Building at Texas A&M University, following the guidelines provided by the EC-Drill™ Technology Providers and available literature. The model was scaled to 1/3 of actual riser size and initial tests were done using water to prove the successful design and installation of the equipment. Following this, the scaled model was prepared and calibrated to accommodate clear drilling mud to provide visual study of the gas migration phenomenon. However, due to the limitations of the pump rates and flow meters along with the use of water as a drilling mud, the tests were unsuccessful in fully mitigating the gas migration issue, leading to the need of upgrading the equipment that were used to run the tests.

DEDICATION

To my Mother and Father for the love and support throughout my life

If not for them none of this would be possible

To my brothers and sisters for the support and memories

To all my friends and family whom I love and cherish

ACKNOWLEDGEMENTS

I would like to thank my committee chair Dr. Jerome J. Schubert for providing me with funding and support throughout my Master's degree. If it was not for his advice on taking his advanced lectures, I would not have been introduced to offshore drilling and work on the research I have completed for this thesis.

I would like to thank my committee members Dr. Catalin Teodoriu and Dr. Charles P. Aubeny. I would like to thank John Cohen and Roger Stave with Enhanced Drilling and Dr. John-Morten Godhavn and Sturle Gaassand with Statoil for the information and guidance they provided with designing the lab and running experiments.

I would like to thank John Maldonado, Andrew Johns, Matthew Bell, Michael Callaghan, Pedro Cavalcanti de Sousa, Vincent Doczy and Jeffrey Zhang for all the help and support they provided with designing and building my lab.

I would like to thank Idris Kirdemir for being there throughout all of my life and providing support and assistance whenever I needed it. I would like to thank Gultekin Cinar for the guidance and training he provided prior to and during my education at Texas A&M University. I would like to thank Ms. Violetta Cook for all the guidance and support throughout my education at Texas A&M University, and being available to speak with, whenever I needed her advice. I would like to thank Mr. Fred Dupriest and Dr. Samuel Noynaert for the support and advice they provided and being available to answer questions regarding my research and career. I would like to thank Stephen Spafford, for answering questions and providing help when I began studying at Texas A&M University to become a Petroleum Engineer.

Thanks to all my friends for all the entertaining memories and the endless friendship they have provided me with.

NOMENCLATURE

AADE	American Association of Drilling Engineers
BHP	Bottom Hole Pressure
BML	Below Mud Line
DGD	Dual Gradient Drilling
ECD	Equivalent Circulating Density
GOM	Gulf of Mexico
IADC	Association of Drilling Contractors
JIP	Joint Industry Project
MW	Mud Weight
MPD	Managed Pressure Drilling
MRJ	Modified Riser Joint
MRL	Mud Return Line
NPT	Non-Productive Time
OBM	Oil Based Mud
P	Pressure
P_f	Fracture Pressure
P_{hyd}	Hydrostatic Pressure
P_p	Formation Pressure
Q	Flow Rate
SPE	Society of Petroleum Engineers

SPM	Subsea Pump Module
T	Temperature
t	Time
TVD	True Vertical Depth
WBM	Water Based Mud

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1. INTRODUCTION AND LITERATURE REVIEW

The Oil and Gas industry as a whole has always been seeking to improve its offshore drilling technology. Tight pore and fracture pressure windows and extremely low tolerance for drilling fluid errors, combined with limited storage capacity, possible environmental effects and great water depths have caused industry to seek new and safer ways of drilling these wells. The advances in the offshore drilling technology have allowed for the maturation of the shallow and simple hydrocarbon reservoirs, this coupled with the increase in demand for energy has resulted in the requirement to find efficient methods of extraction for reservoir below deep (1500 – 5000 ft. water column) water and ultra-deep waters (5000 ft. and deeper).

The presence of large water bodies above the oil or gas bearing formations results in greater uncertainty in the drilling process, thus causing tighter margins for error in drilling operations. Additionally, drilling in deep water through formations with low reservoir pressures in depleted fields or in abnormally pressured formations presents great challenges when using conventional drilling methods.

An alternative class of drilling methods to conventional drilling methods, Managed Pressure Drilling (MPD), has proven to be successful in drilling challenging wells in the past. Safety issues, Non-Productive Time (NPT), drilling costs, reservoir damage and pressure window limitations are all considered important factors in the selection of the method for drilling. Various MPD types exist for different pressure and formation issues, however there is no single MPD method that can be used for all cases.

1.1. Managed Pressure Drilling

The development of the unconventional reservoirs and the requirement for horizontal drilling in shale reservoirs, has made pressure management while drilling an important application.

MPD has been defined by the International Association of Drilling Contractors (IADC) as "*An adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole pressure environment limits and to manage the annular hydraulic pressure profile accordingly. It is the intention of MPD to avoid continuous influx of formation fluids to the surface. Any influx incidental to the operation will be safely contained using an appropriate process*." (Committee 2011)

Drilling in deep and ultra deep offshore areas often encounter major difficulties successfully drilling to the Total Depth (TD). As the depth increase the overburden increases and the drillable Pore Pressure (P_p) and Fracture Pressure (P_f) window gets tighter, making maintaining a Bottom Hole Pressure (BHP) within this window more challenging. The consequence of increasing the BHP over the Fracture Pressure, is fluid loss to the formation, causing drilling mud to invade the pores and as the pressure continues to increase, a total loss of circulation occurs, causing irreparable damage to wellbore integrity. On the other hand, if the BHP reduces to below the Pore Pressure, formation fluid will enter the wellbore, causing influxes which may lead to a blowout. For these reasons a methods of dynamically managing the pressure are required.

MPD was developed to improve well control, reduce cost by minimizing non-productive time and drilling flat time, improving hole integrity, setting deeper casing points, reducing the amount of needed casing strings and resulting with a larger diameter production casing. These are all achieved using methods that utilize back pressure control, lighter or heavier mud depending on the method to manage the Equivalent Circulating Density (ECD), fluid rheology, annular fluid level in the riser, Circulating Friction, hole geometry. These methods are; Constant Bottom Hole Drilling (CBHD), Pressurized Mud Cap Drilling (PMCD) and Dual Gradient Drilling (DGD).

1.1.1. Constant Bottom Hole Pressure

In CBHP the BHP is kept constant by applying a back pressure using the choke or a rotating control device (RCD). This method keeps the BHP constant while allowing for lower mud weights than conventional. Choke is applied while circulation is stopped to compensate for frictional loss (Nas et al. 2009).

1.1.2. Pressurized Mud Cap Drilling

PMCD is used when there is a severe loss of circulation case. In this method there are no returns to the surface. Pressure is maintained above the formation pressure with the use of the fluid column in the annulus along with the applied backpressure. In this method a certain level of fluid loss is acceptable. (Medley and Stone 2004)

1.1.3. Dual Gradient Drilling

In DGD, the BHP is kept within the pore and fracture pressure window by manipulating the fluid located in the annulus. In offshore operations, this is achieved by lowering the mud level and diverting it through a subsea pump attached to the riser, or by pumping the mud at the seafloor to the rig through a subsea pump located on the seafloor. There are alternative methods where gas or hallow glass maybe pumped at the BOP to lower the density of the fluid in the riser.

DGD was developed as a result of multiple Joint Industry Projects (JIP) which led to the variations of DGD such as Subsea Mudlift Drilling (SMD), EC-Drill™, Riserless Mud Recovery (RMR), Dilution Method and the Hollow Sphere Method.

The SMD Method is also called the full DGD method. In SMD, the riser is filled with seawater while the annulus below the mud line is filled with drilling mud. The mud is returned to the surface through subsea pumps. The pressure is managed by adjusting the flow rate of the subsea pump module. This method was developed as the need for reaching deeper reservoirs and drilling in deeper water depths. This method provides the operator with a safer, reliable and economical way of achieving success in offshore drilling.

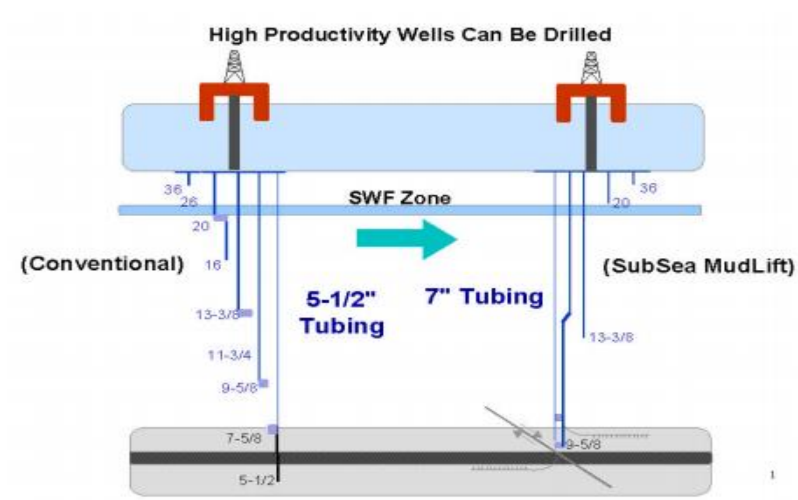

Fig. 1— Comparison of the Casing Program for Conventional Drilling and SMD Methods (Smith et al. 2001)

Fig. 1 clearly displays the casing design for a conventional and a SMD well. The SMD method provides the opportunity to set casings deeper and use fewer casing strings ultimately resulting with a larger production string.

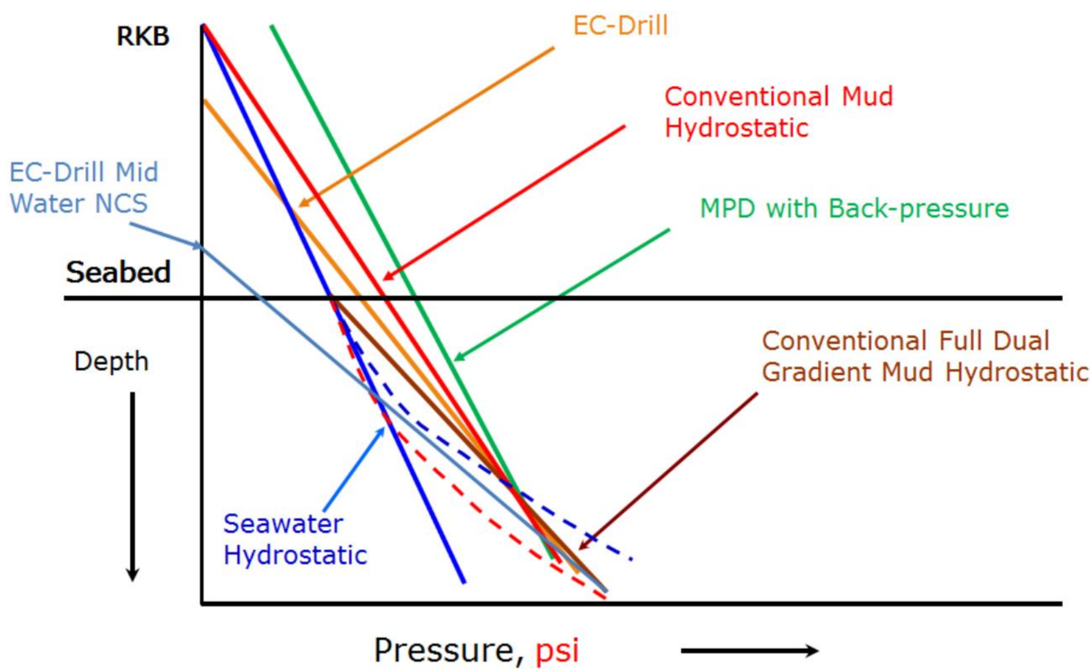

Fig. 2— The Relationship Between Various MPD Techniques and Pressure Gradient (Malt and Stave 2014)

Fig. 2 compares the Pressure profile with respect to depth using Conventional Drilling, MPD with Back Pressure, EC-Drill™ and the SMD Method. Each method serves a different purpose but the end goal is to achieve success by maintaining the BHP within the Pore and Fracture Pressure window (Malt and Stave 2014).

1.2. EC-Drill™

EC-Drill™, an offshore drilling technology, currently provided by Enhanced Drilling, is a variation of the DGD method.

This method was developed for application on floating vessels with very minimal modifications. The EC-Drill™ system operates by controlling the mud level in the annulus of the riser, providing a dual gradient system by creating a void in the top section of the riser where mud and air are the two gradients.

The dual gradient system in EC-Drill™ is achieved by attaching a Subsea Pumps Module (SPM) to the riser at the pre-determined depth. The Subsea Pumps, create an alternate route for the mud to return to the rig floor (Godhavn et al. 2015). The Subsea Pump Module (SPM) is attached onto the riser using a Modified Riser Joint (MRJ). The MRJ provides a suction port where the returning mud is diverted into the SPM and pumped up to the rig floor through a Mud Return Line (MRL). The MRJ contains a set of pressure transducers which allow the operator to determine the mud level within the riser. As the fluid level drops, the hydrostatic pressure at the point of the MRJ drops, conversely, as the fluid level rises, the hydrostatic pressure at the point of the MRJ rises correspondingly. The pressure data is then used to determine the required flowrate of the EC-Drill™ SPM to maintain a desired BHP (Mirrajabi et al. 2012).

Fig. 3—EC-Drill™ Subsea Pump Module (Mirrajabi et al. 2012)

Fig. 3 shows an image of the EC-Drill™ Subsea Pump Module which was described in SPE 151100 as a three-stage SPM powered by 400 hp electric motor. The pumps have proven successful in water depths of 4921 ft. (1500 m) and handle drilling mud with solids and 10% gas. (Mirrajabi et al. 2012)

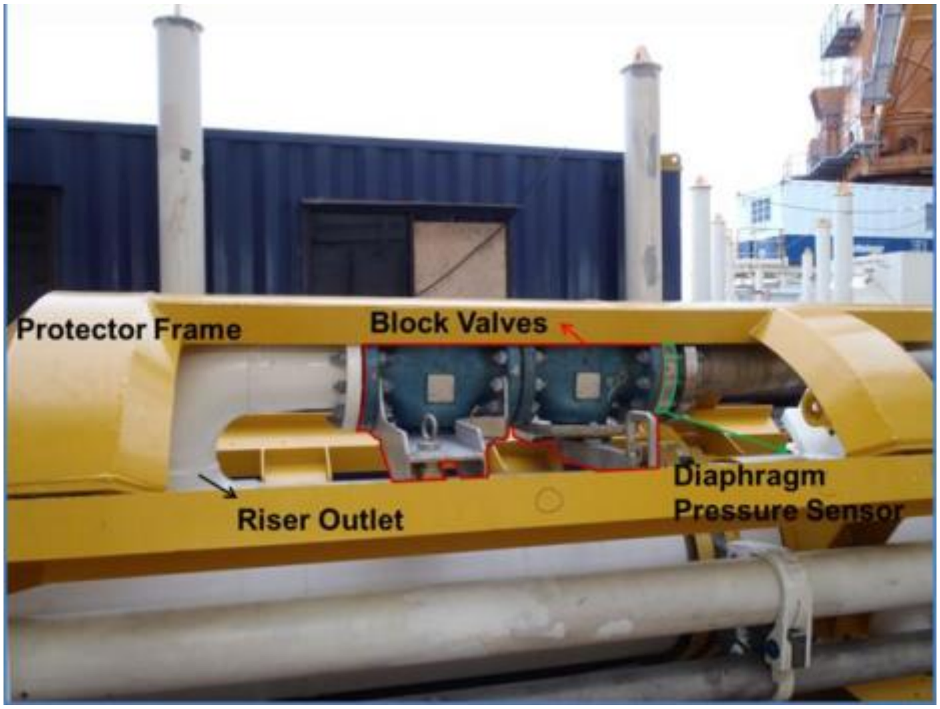

Fig. 4—EC-Drill™ Modified Riser Joint (Mirrajabi et al. 2012)

Fig. 4 illustrates the Modified Riser Joint (MRJ) which is used to divert the returning fluid in the annulus to the Subsea Pump Module. The figure illustrates the Block Valves which isolate the pumps when needed to return to conventional riser drilling. The MRJ also houses Pressure Sensors which provide the pressure data to automatically adjust the SPM rate.

The sensitivity of the pressure transducers and the system provides the opportunity to instantly determine the smallest changes in the wellbore and rapidly remediate by manipulating the ECD via the EC-Drill™ SPM. With this quick response, kicks are circulated with very little pit gain and loss of circulation situations are handled with minimal losses.

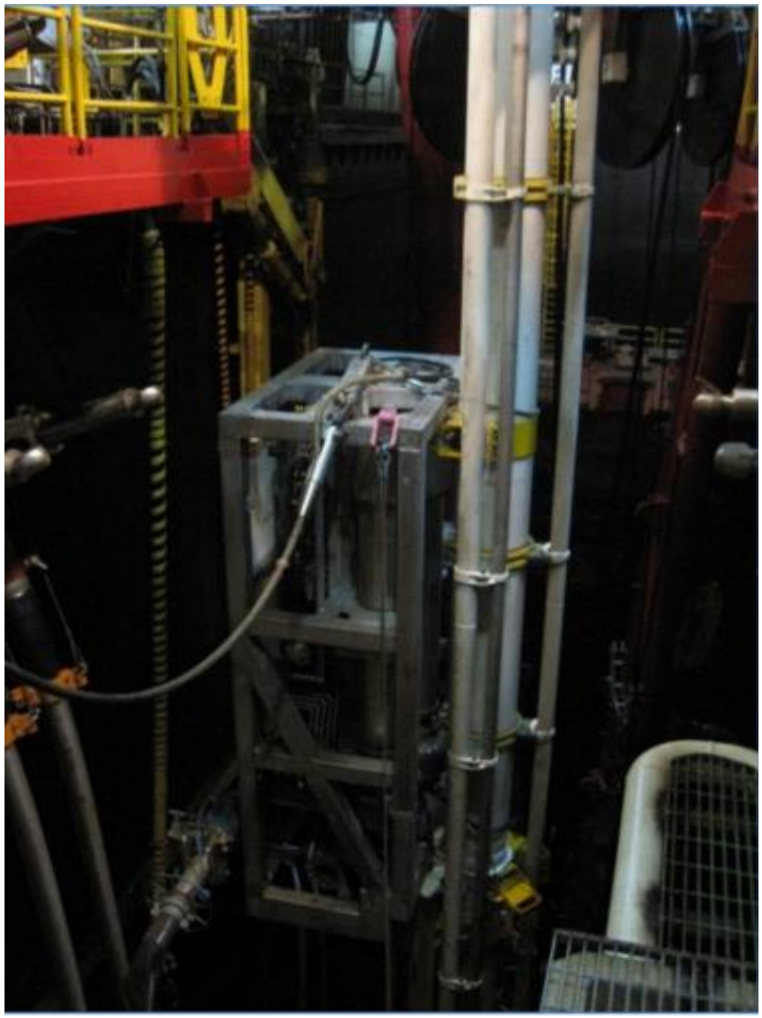

Fig. 5—Running Riser with SPM (Mirrajabi et al. 2012)

By raising or lowering the mud level in the riser, the hydrostatic of the mud column is manipulated, which allows the operator to control the BHP and the Equivalent Circulating Density (ECD). **Fig. 5** illustrates running of the SPM attached onto the MRJ.

There are many benefits to applying this method such as the early detection of loss and gain of fluid, allowing for a dynamic pressure control to maintain a BHP between the tight pore and fracture pressure windows.

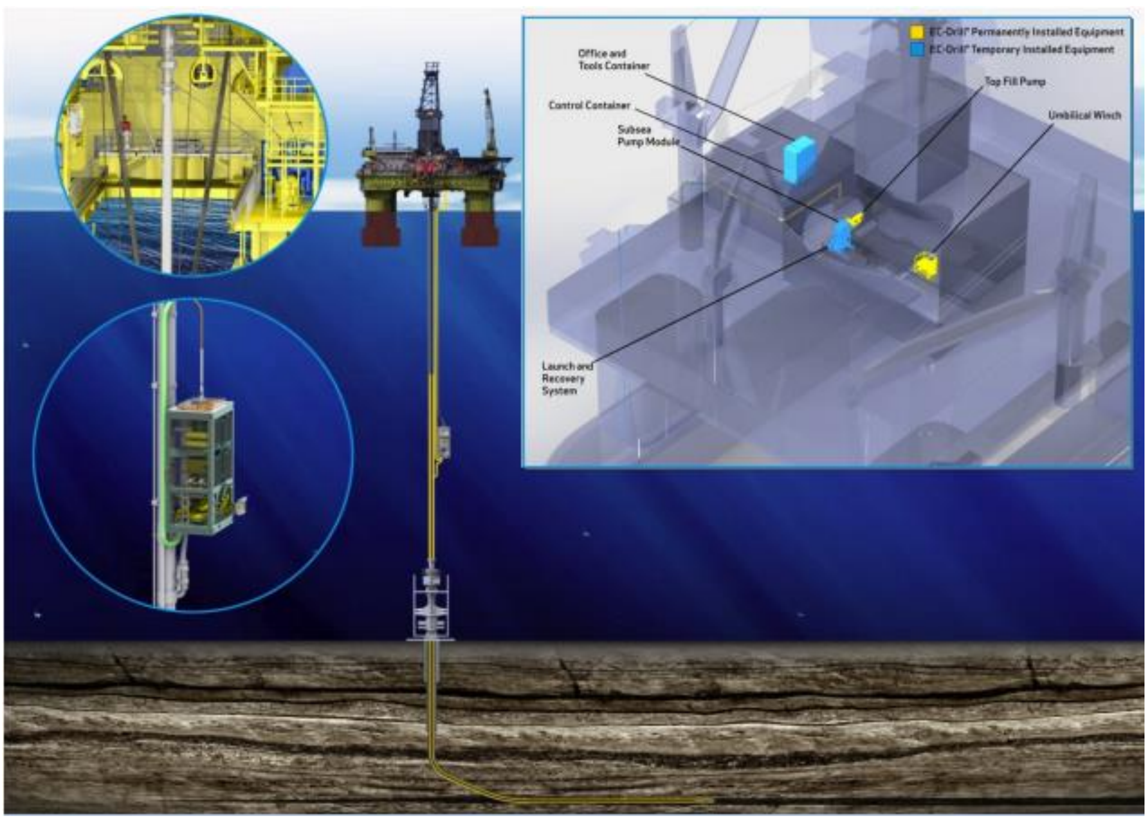

Fig. 6—EC-Drill™ Configuration on COSL Innovator (Fossli and Stave 2014)

Fig. 6 shows the EC-Drill™ Operational Configuration of the equipment. The Subsea Pump Module (SPM) is attached to the riser to divert returning fluid through a Mud Return Line (MRL) instead of the conventional riser method. Fig. 6 was taken from SPE Paper 169178 and demonstrates the configuration of the EC-Drill™ on the COSL Innovator which drilled a pilot EC-Drill™ well in the Troll Field (Fossli and Stave 2014).

(Mirrajabi et al. 2012) gives example of wells that were drilled in the ultra-deep Eastern GOM. The first exploration well failed to achieve the desired depth due to total loss of circulation. The well was drilled using a WBM with the lightest MW possible. The naturally fractured carbonate formation started taking in the drilling fluid causing to a total loss of circulation. The location of the second well had similar characteristics, a reservoir that is vuggy and has cavities. To prevent the issues that caused the failure in the first well, the EC-Drill™ method was used due to its capabilities of lowering the BHP by lowering the mud level in the riser and compensating for frictional loss. The use of the EC-Drill™ method prevented the loss of circulation in formations with very low pore pressures.(Mirrajabi et al. 2012)

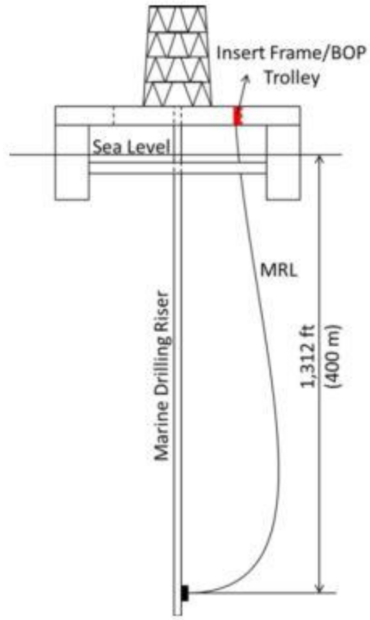

Fig. 7—Subsea Pump System (Mirrajabi et al. 2012)

Fig. 7 displays a simple illustration of the EC-Drill™ System, with the EC-Drill™ SPM located at 400 m (1,312 ft.) (Mirrajabi et al. 2012). The dramatic difference in the results due to application of the different methods compels greater attention to the problem of gas migration in drilling operations.

1.3. Gas Migration

Gas migration is a crucial subject which requires further investigation, while there exists literature on gas migration, the information given is sometimes conflicting with laboratory and actual tests. As a result, these studies have not yielded an accurate gas migration model.

The rule of thumb for gas migration velocity in a vertical well is about 15 ft/min, however some studies with moderate to greater gas concentrations (>10% gas concentration) have yielded migration velocities as high as 100 ft/min. (Johnson et al. 1995)

(Johnson et al. 1995) compares literature on gas migration studies done by Johnson and White, where they have demonstrated the 100 ft/min result using actual drilling mud in standard well geometries. The velocity of gas migration is lower when water is used as the medium due to the low viscosity. This is due to the effect of viscosity on the gas bubbles, wherein the greater the viscosity the greater the hindrance on bubble break up allowing for larger bubbles to travel up. Larger bubbles migrate faster than smaller bubbles through drilling fluids. (Johnson et al. 1995) also reviewed experimental work reported in (Rader et al. 1975) where the authors claim similar results from a 3.7m (12ft) flow loop and a 1800 m (6000 ft.) well. (Johnson et al. 1995) also considered results reported in (Rommetveit and Olsen 1989) in large scale test from a 1500 m (5000 ft.) deep test well. The measurements were done between pressure transducers installed at different depths and the time of flight method was used to measure the migration velocity which was 0.55 m/s (110 ft/min). (Johnson et al. 1995)

Slip velocity of the gas bubble is an important variable that defines the migration process however even this has multiple uncertain variables such as the density of the drilling fluid, the rheological properties of the fluid, the size of the gas bubble and the geometry of the gas bubble. (Lloyd et al 2000).

In order to enhance understanding of gas migration further studies have to be performed and actual experiments from wells must be performed. (Rommetveit and Olsen 1989), (Hovland and Rommetveit 1992) report a study on 24 full scale gas kick experiments that were performed on the offshore drilling rig “Ullrigg” in Stavanger by Rogaland Research in 1988. The rig drilled 3 wells and the data for these wells are in **Table 1**.

Table 1—Test Wells Drilled by Ullrigg in Stavanger (Rommetveit and Olsen 1989)

Well #	Measured Depth (meters)	Maximum Inclination (degrees)
1	1000	7
2	2230	63
3	340	0

Table 1 shows the information provided in (Rommetveit and Olsen 1989) about the wells that were drilling in Stavanger City by Ullrigg. Of 3 wells reported, the kick experiments were performed on well #2. The 9 5/8” Casing was set with a 7” extension with the casing shoe at 1510 m MD. A bullnose was welded on to the 7” extension to prevent exchanging of fluid. The experiments were performed with a conventional drill string; 5” drill pipe, 100 m of 6 ½” drill collar and 8 ½” drill bit. (Rommetveit and Olsen 1989)

Figs. 8 and 9 provide detailed description of the well path and the experimental setup for these experiments.(Rommetveit and Olsen 1989)

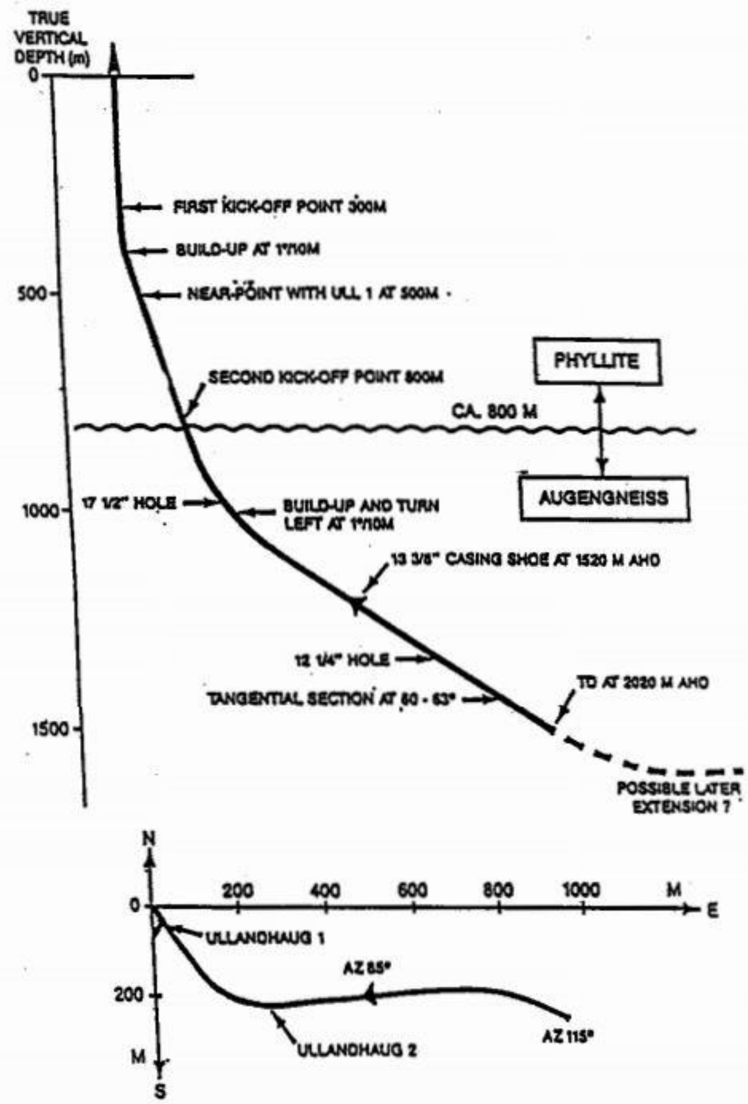

Fig. 8—Ullrigg Well #2 2D Well Diagram (Rommetveit and Olsen 1989)

The well was split into six (6) sections and pressure sensors were used all along the well. Also a flow meter was used to measure the mud flow rate and a gamma densitometer which was clamped on to the choke line to measure densities ranging from air to the heaviest mud density possible. (Hovland and Rommetveit 1992)

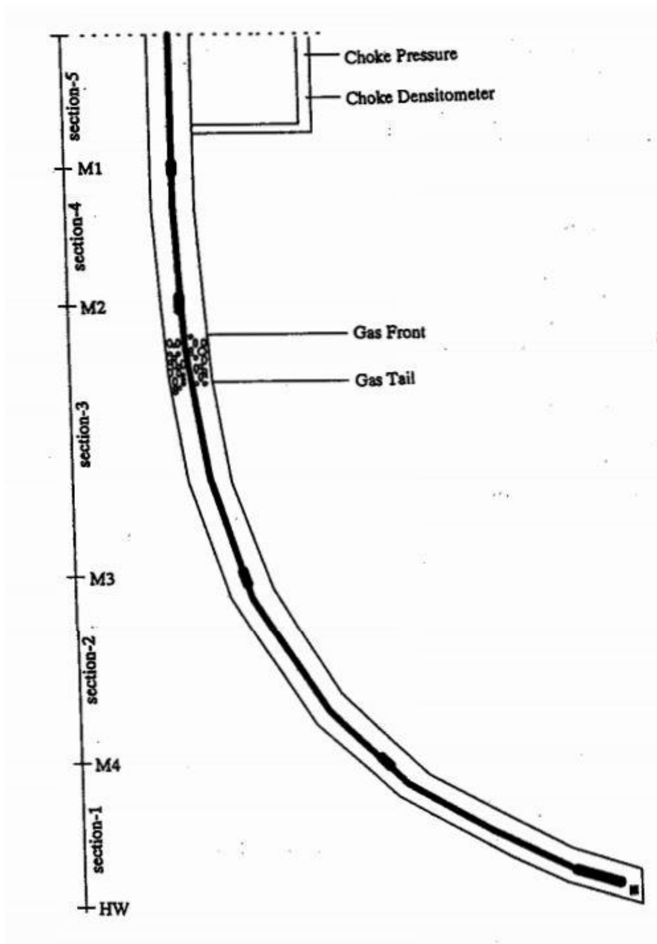

Fig. 9—Well Geometry and the Position of Sensors (Hovland and Rommetveit 1992)

2. METHODOLOGY

The method studied in this thesis is illustrated in **Fig. 10**, where the riser is filled with fluid from the top. This method requires knowledge of the flow rates, the gas migration velocity, the drilled gas, the mud level in the riser and the suction rate at the pump mounted on the riser.

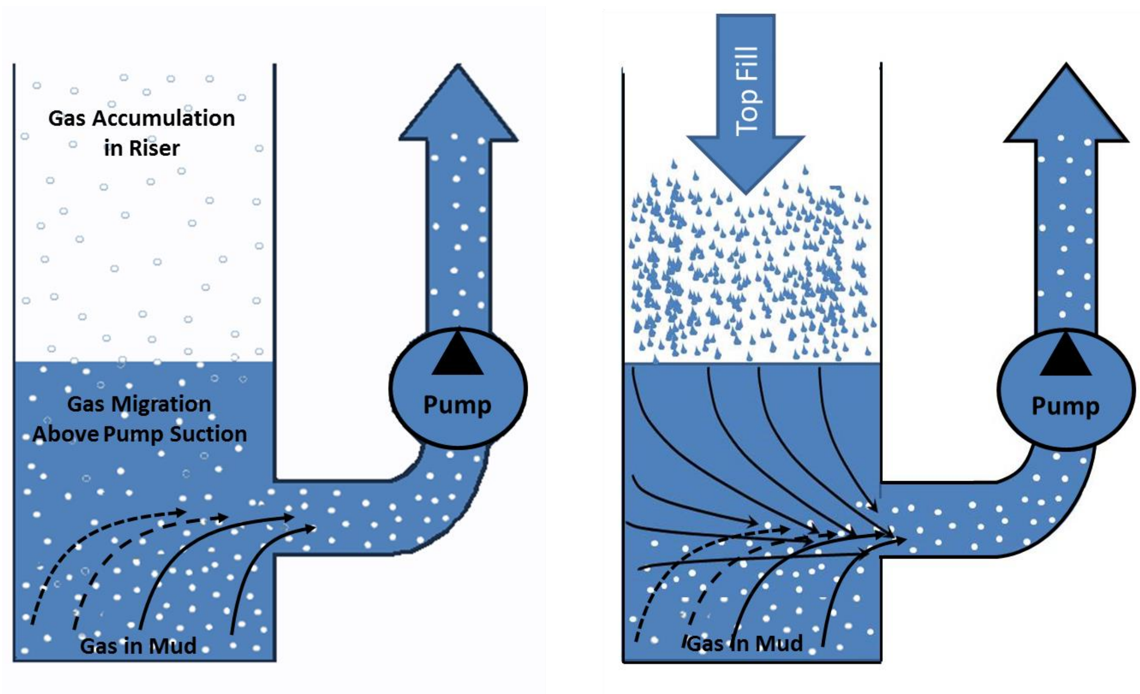

Fig. 10—Top Fill Method (AGR 2013)

As seen in Fig. 10 the gas migrates to the top of the riser, the accumulation of gas causes major hazards. Injecting fluid from the top will cause a downward flow in the riser pushing down the drilled gas. The downward flow has to be great enough to prevent the gas from flowing up beyond the riser pump.

In order to achieve this result the amount of drilled gas was calculated along with the migration velocity of the gas bubble through the drilling fluid.

The experimental setup that was built to test the method is presented in **Fig. 11**.

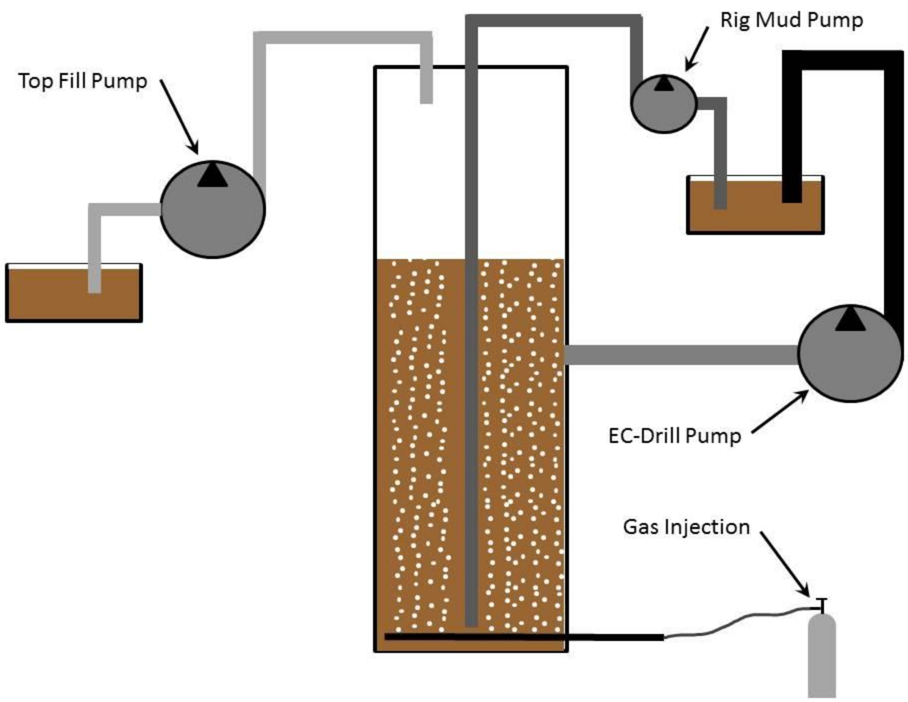

Fig. 11—Experimental Setup Schematic (AGR 2013)

The lab setup is a small-scale version of an actual marine riser. A 6" clear PVC pipe was used to simulate the riser, along with 55 gal/min pumps to simulate the top fill injector and the pump mounted on the riser. Due to safety considerations, air and non-flammable gases was used instead of methane.

The gas injection rate at the bottom of the riser were set according to the results from calculations using set parameters for formation properties and gas properties. The test fluid used was clear water and the riser model was built to be 27 ft. long.

Initially, the tests were ran with pumps at maximum rate and then after determining the limits of the riser mode, the flow rates were varied using the VFDs. This provided the opportunity to collect data and analyze gas migration through water.

3. DESIGN

3.1. Lab Setup

A specific to research lab setup was built in the University Services Building at Texas A&M University. This building has a 30 ft. ceiling clearance allowing for a lab scale riser system to be installed.

This facility contained a support system that could be lifted from horizontal to vertical using a winch allowing tests to be run at any inclination. This support system was used to perform the necessary experiments and research for the lab. **Fig. 12** displays an image of the riser simulator mounted on the support system.

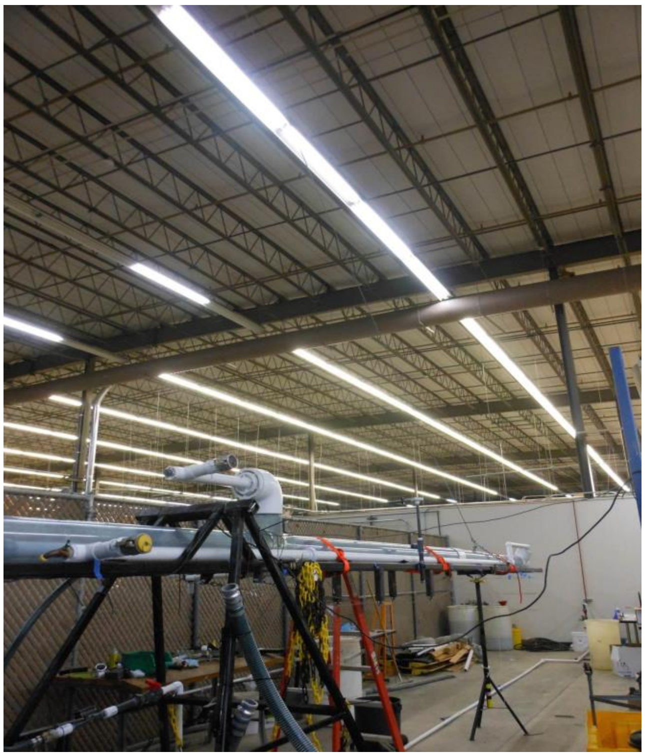

Fig. 12—Support System

3.1.1. Phase 1: Evaluation of Available Structure and Equipment

The initial phase involved extensive investigation and evaluation of the facility capabilities, support system and existing equipment. This phase was important in order to reduce the cost involved in building the scaled riser.

After evaluation of the facilities and available equipment, 6” PVC Pipe was chosen to couple with the already existing support system. So, the actual 19½” riser case was scaled down to a 6” riser system.

Once a lab scale for the riser was established, pump size and flow rates and drill pipe size were also determined through calculation. In order to reduce costs, existing equipment was reused, and hydraulic calculations were performed accordingly.

The available power of the facility was limited to 110 V and a work order was placed to upgrade the power supplied to the lab to 220 V. The upgrade was sufficient enough for two existing centrifugal pumps to be used.

Fig. 13 shows the pumps that were selected as mud pumps. These pump flowrate for the setup with the annulus of the 6” scaled riser with a 2” drill pipe were determined to be analogous, to equal the linear flow velocity of the actual case with a 19.5” Riser and a 6” drill pipe with pumps running at 1000 GPM.

Fig. 13—Scaled Pumps for Riser Simulator

Fig. 14 displays the specification of the pumps.

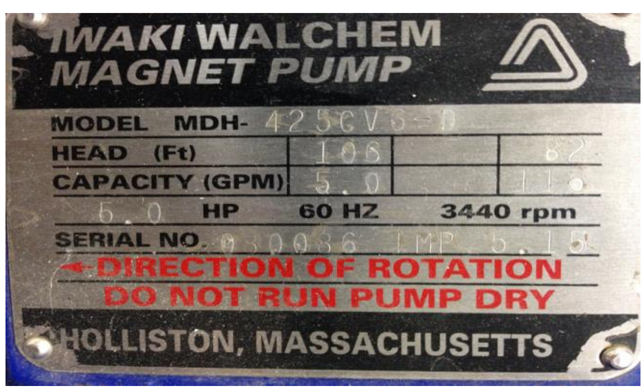

Fig. 14—Pump and Motor Specifications

The Pumps in Fig. 14 were used as the circulation mud pump and the Ec-Drill™ pump. The pumps have a 5 HP motor and provide a Flowrate of 115 GPM at a hydraulic head of 82 ft. The pumps provide a 1.5” outlet and a 2” inlet. So the drill pipe and return line were scaled down to 2” pipe diameter.

Once the pump selection was completed, Variable Frequency Drives (VFD) were needed to supply power and control the frequency of the pump motor. VFD’s allow the operator to adjust the flow rate during circulation. The power upgrade also included installation of two VFD’s.

Fig. 15—Variable Frequency Drives (VFD)

Fig. 15 displays the VFD's used for this simulator to control the pump rate.

When the Riser system was initially placed on the support system it was observed that the support system was flexing over the pipes when the system was brought into a vertical position. This could lead to fatigue and complete failure of the Riser System causing major damage and injury in the lab. Thus, the support system was modified by the addition of a cable tensioner via welding to reduce riser flexibility and increase the rigidity of the support system.

3.1.2. Phase 2: Hydraulic Calculations

As stated in the previous section, the scaled riser was scaled down from the actual case of 19.5 inch inner diameter marine riser, and a 6 inch outer diameter drill pipe. The scaled riser dimensions were limited by the height of the lab and the capacity of the support system. The length of the scaled riser is 27 feet, with a diameter of 6 inches using clear PVC pipe. The scaled drill pipe was simulated with a 2 inch OD PVC Pipe. This dimension was selected to dovetail with the discharge diameter of the Circulation Pump.

The basis flow rate was 950 GPM. This rate was scaled down for use with the scaled model. The scaling factor was based on the annular velocity of the fluid profile. The calculation method for annular velocity is given in the API Recommended Practices 13D.

$$V_a = \frac{24.51 * Q}{d_h^2 - d_p^2}$$

Where;

V_a: Annular Velocity (ft/min)

Q: Flow rate (GPM)

d_h: Hole Diameter (in)

d_p: Pipe Outside Diameter (in)

The annular flow velocity of the fluid at 950 GPM through a 19.5" Riser and a 6" Drill Pipe is calculated below:

$$V_a = \frac{24.51 * 950}{19.5^2 - 6^2} \cong 68\ ft/min$$

The flow rate through the Riser Simulator has to create an annular flow velocity equal to 68 ft/min.

Rearranging the equation:

$$Q = \frac{V_a * (d_h^2 - d_p^2)}{24.51}$$

Plugging in the values:

$$Q = \frac{68 * (6^2 - 2^2)}{24.51} \cong 89\ GPM$$

Running the pumps for the scaled model at 89 GPM is sufficient to create the 68 ft/min flow velocity through the annulus of the scaled riser.

3.1.3. Simulator Design and Pump Placement

After completing the hydraulic calculations, having the winch replaced and welding the stiffeners to reduce the flexibility of the rack, the pipes that formed the riser were connected and the supply lines were built.

To provide movement flexibility when needed, the pumps and mud tank were installed on a skid that was built from two I beams.

Fig. 16—Skid for the Pumps and Mud Tank

Fig. 16 is a photo of the skid, with the pumps and Mud Tank built for the riser simulator.

4. RESULTS AND DISCUSSION

This section presents the results of experiments ran and discusses the implications of these results.

The equipment limitations along with the calibration data are covered separately in Appendices C, D and E sections of this thesis.

The following tests were run with the scaled riser in the full vertical configuration. The tests were split into 4 sets, with the Circulation Pump Frequency as a base case, and varying the EC-Pump Frequency for each case.

For all cases presented in this thesis, water was used as the Drilling Fluid and air used as the gas influx.

Two pressure sensor points along the riser model are logged. The first point is located at the base of the riser, where the circulation pump is attached to the riser; the second point is located at the discharge where the EC-Pump is attached to the riser model. The data from the two points is processed to determine the mud level. In addition the pressure data was used to track the gas migration, video confirmation of results was attempted. The pressure data will additionally be used to optimize the pumps and create a feedback loop allowing the EC-Pump to adjust its rate to maintain a mud column level selected by the user for any circulation rate input also selected by the user.

The minimum Circulation Pump Frequency that can be used with this system is 32.5 Hz, any frequency lower than this would not provide the necessary head preventing the fluid level from rising to the point of interest for analysis.

Fig. 17—Riser Simulator Setup

The **Fig. 17** is an image of the scaled riser with attachments plugged while testing.

Table 2—Gas Migration Test Inputs and Outputs

Test #	Circulation Pump		EC-Pump		Gas Injection Rate (SCFM)	Top Fill Rate (GPM)	Annular Fluid Height (ft.)	Time (s)
	Frequency (Hz)	Rate (GPM)	Frequency (Hz)	Rate (GPM)				
1-a	32.5	111.6	0	111.8	<0.5	1.8	15	142.1
2-a	35	120.5	0	122.2	<0.5	1.8	18	107.5
2-b	35	125.1	5	126	<0.5	1.8	17.5	80.9
2-c	35	132.2	10	131.6	<0.5	1.8	17	79
2-d	35	139.5	15	138.7	<0.5	1.8	15.5	108.5
2-e	35	148.6	20	147.8	<0.5	1.8	14.5	77.3
3-a	37.5	142	10	142.4	<0.5	1.8	18	76.3
3-b	37.5	151	15	149.3	<0.5	1.8	17.5	71.7
3-c	37.5	157.3	20	158	<0.5	1.8	15.5	72.4
3-d	37.5	165.2	25	165.7	<0.5	1.8	13.5	130.8
4-a	40	147.2	7.5	147	<0.5	1.8	24	116.9
4-b	40	152.5	10	152.8	<0.5	1.8	23	75
4-c	40	155.7	12.5	154.1	<0.5	1.8	22.5	74.1
4-d	40	157	15	157.1	<0.5	1.8	21	73.9
4-e	40	160.1	17.5	161.1	<0.5	1.8	19	85.3
4-f	40	165.9	20	165.7	<0.5	1.8	18	73.7
4-g	40	168.2	22.5	170.4	<0.5	1.8	16.5	82.9
4-h	40	170.8	25	173.5	<0.5	1.8	15	96.9
4-i	40	174.7	27.5	177.3	<0.5	1.8	13.5	88.5

Table 2 contains the input and output data for the gas migration tests performed for this research. Given inputs of frequency of circulation pump and Ec-pump as well as

gas injection rate and top fill rate, outputs of rate of circulation pump and Ec-pump as well as annular fluid height were generated by the model.

Although some gas bubbles were diverted to the EC-Drill™ outlet, the tests failed to manipulate the gas migration and fully direct the gas bubbles to the EC-Drill™ Outlet. The fact that some of the gas was diverted into the EC-Drill™ Outlet, led to the conclusion that the current testing model may provide a successful result if the equipment at the testing facility, the rheology of the drilling mud and the rate at which the gas was injected were all upgraded.

Below are the resulting flow rate and pressure data collected from each individual test.

4.1. Test Set #1: Full Vertical Test With 32.5 Hz Circulation Frequency

4.1.1. Test 1.a. Results- 32.5-0 Hz Pump Frequencies

After activating the Top fill and the Circulation Pump the system was allowed to stabilize, the data was logged for 142.1 seconds, keeping the EC-Drill™ Pump at 0 Hz. The hydrostatic was the driving factor for discharge allowing the system to maintain a constant Mud Level at 15 ft.

The logged data from Test 1.a is presented in **Fig. 18**.

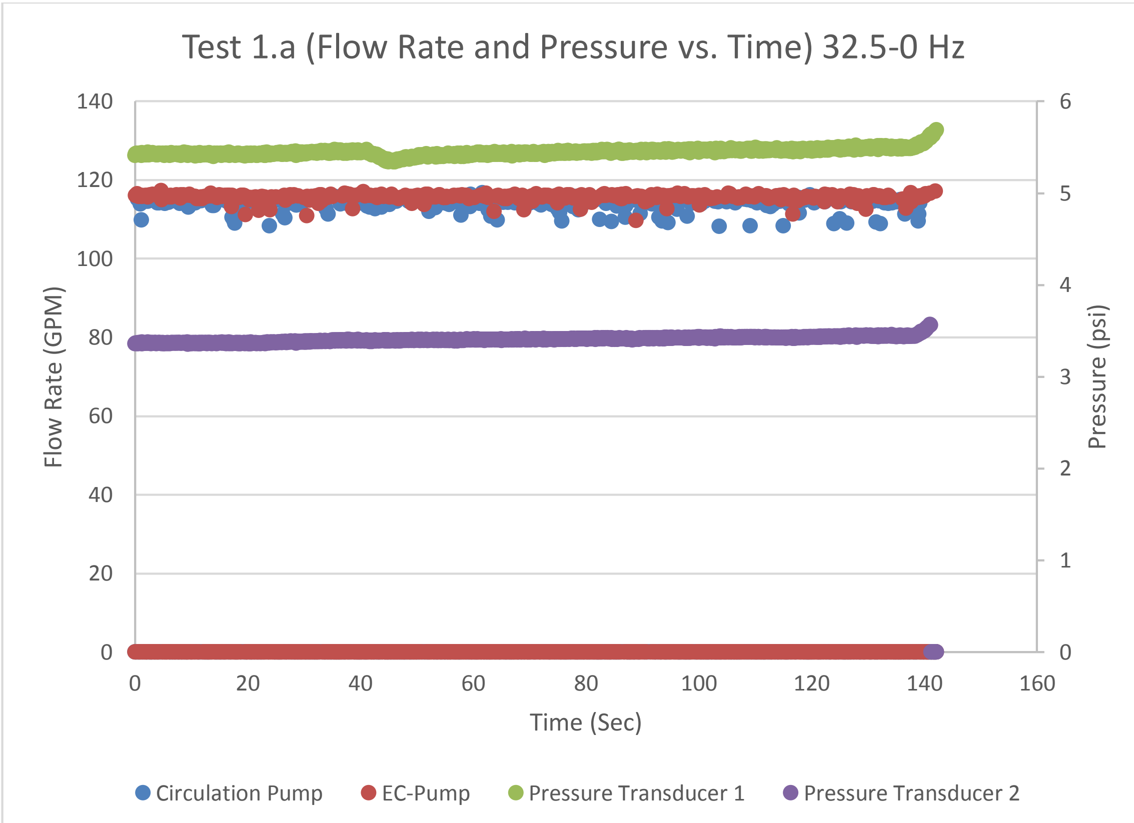

Fig. 18—Test 1.a Circulation and Ec-Pump Rates and Pressure vs Time @ 32.5-0Hz Pump Rates

From Fig. 18, the circulation pump and EC-Pump were maintained at an average rate of 111.6 GPM and 111.8 GPM respectively. The pressure at the base of the riser simulator was stable at 5.45 psi.

From observation of the videos captured by the cameras attached onto the riser simulator, this test failed to prevent gas migration upward into the voided section of the riser. The gas migration was constant, however larger bubbles were formed at the point where the EC-Drill™ Pump is connected to the system due to the air trap.

Fig. 19 shows a closer look at the Pressure Transducer #1, displaying the small fluctuations in pressure.

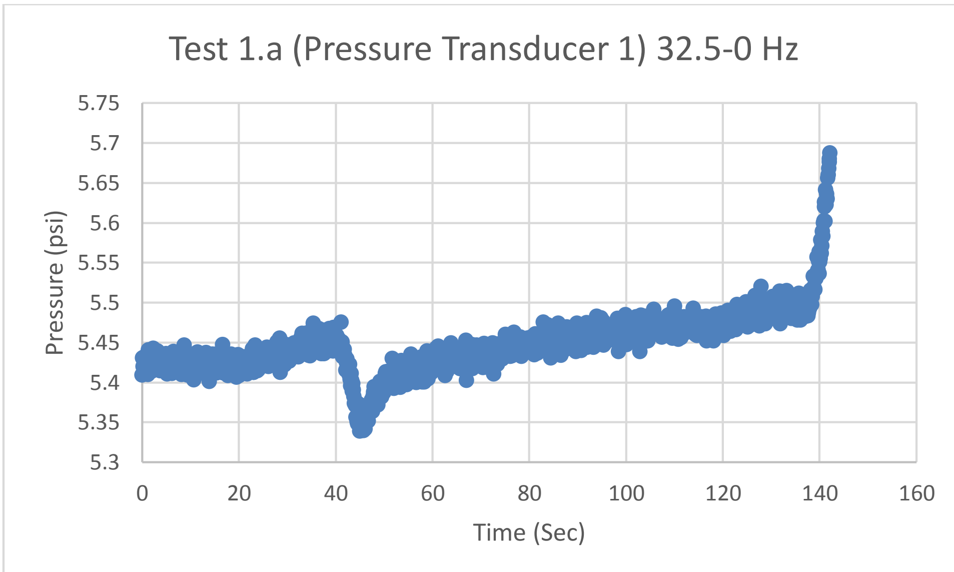

Fig. 19—Test 1.a. Pressure Data from Pressure Transducer 1

Fig. 19 shows the pressure data logged at the base of the Riser Simulator. At first glance, the small fluctuations correspond to large bubble formation at the EC-Pump Discharge and the major fluctuations display the limitations and the effects of the pulsing and fluctuation of the circulation pump in controlling gas migration.

4.1.2. Test 1.b Results- 32.5-5 Hz Pump Frequencies

When the EC-Pump is activated, the discharge rate was high enough such that fluid level was reduced to below 12.5 ft. which is the lower limit of the zone of interest and below the level of the camera. As a result no data was logged and this test was cancelled.

Due to previously obtained results, no further testing was done with Circulation Pump at 32.5 Hz.

4.2. Test Set #2: Full Vertical Test With 35 Hz Circulation Frequency

This test set was performed with the circulation pump frequency set at 35 Hz. From flow meter data this pressure corresponds to a range of 120-155 GPM flow rate.

4.2.1. Test 2.a. Results- 35-0 Hz Pump Frequencies

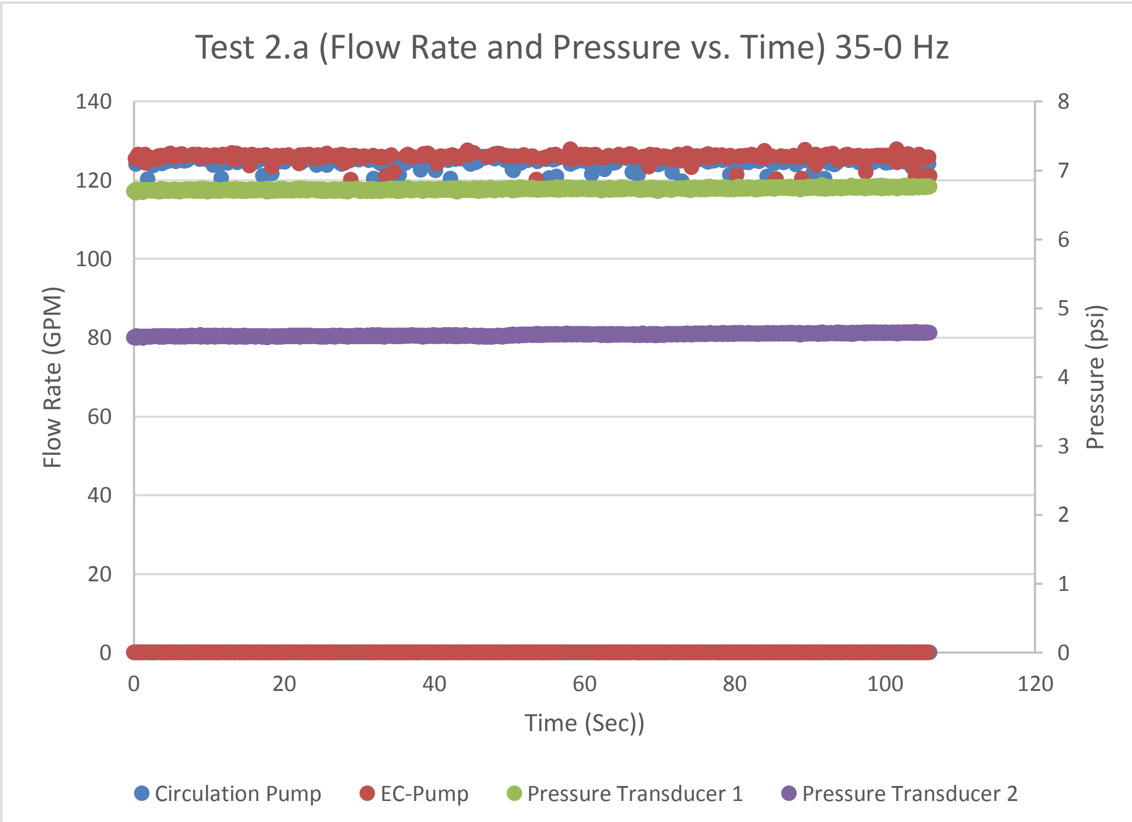

Fig. 20—Test 2.a Circulation and Ec-Pump Rates and Pressure vs Time @ 35-0Hz Pump Rates

As seen in **Fig. 20**, the circulation pump and EC-Pump were maintained at an average rate of 120.5 GPM and 122.2 GPM respectively. The pressure at the base of the riser simulator was stable at 6.73 psi. The graph below shows a closer look at the pressure data acquired from this test.

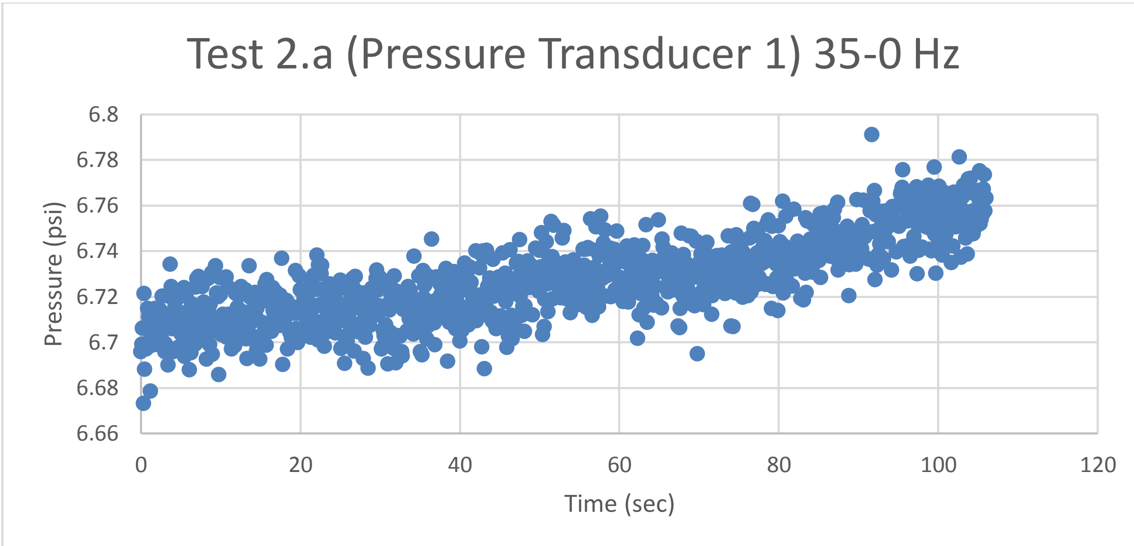

Fig. 21—Test 2.a. Pressure Data from Pressure Transducer 1

From **Fig. 21**, the pressure reading of the transducer shows a steady increase as the air enters the system. The pressure increase is minimal when the overall pressure is taken into consideration. However the fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab.

The fluid level was maintained at 18 ft. and the bubble migration continued through the riser.

4.2.2. Test 2.b Results- 35-5Hz Pump Frequencies

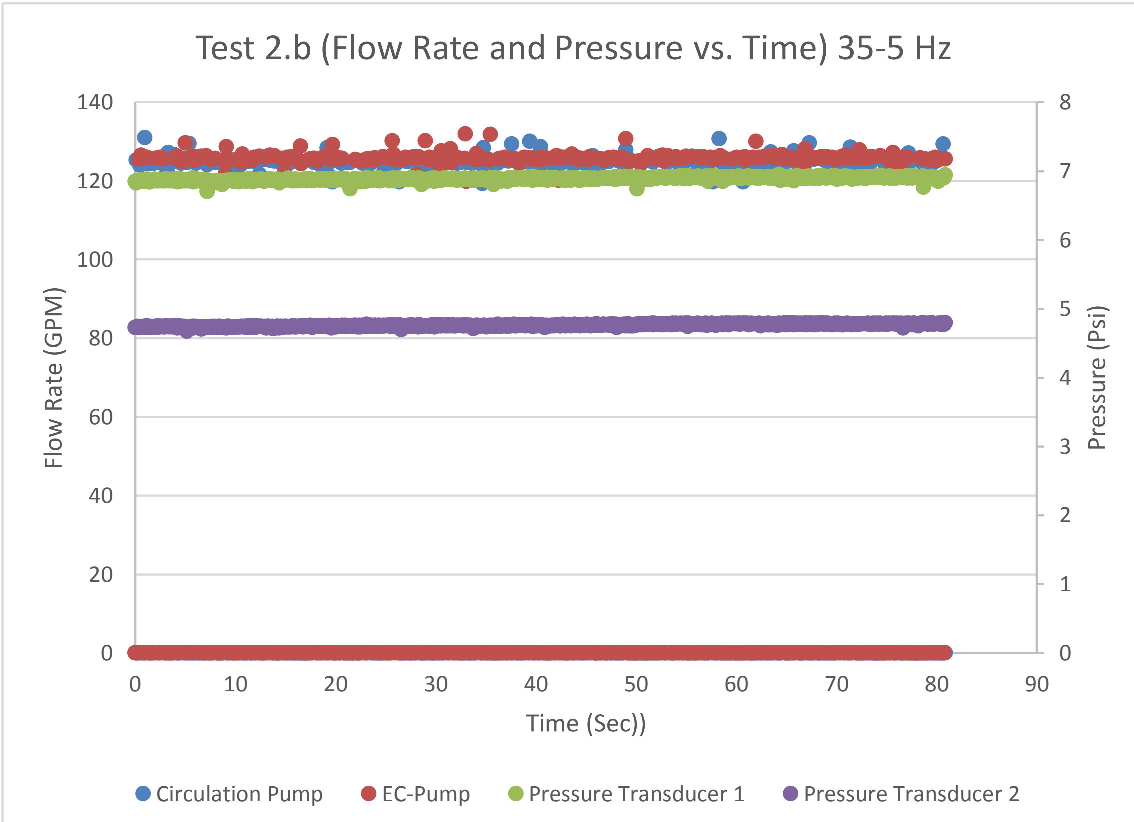

Fig. 22—Test 2.b Circulation and Ec-Pump Rates and Pressure vs Time @ 35-5 Hz Pump Rates

As seen in **Fig. 22**, the circulation pump and EC-Pump were maintained at an average rate of 125.1 GPM and 126 GPM respectively. The pressure at the base of the riser simulator was stable at 6.89 psi. The graph below shows a closer look at the pressure data acquired from this test.

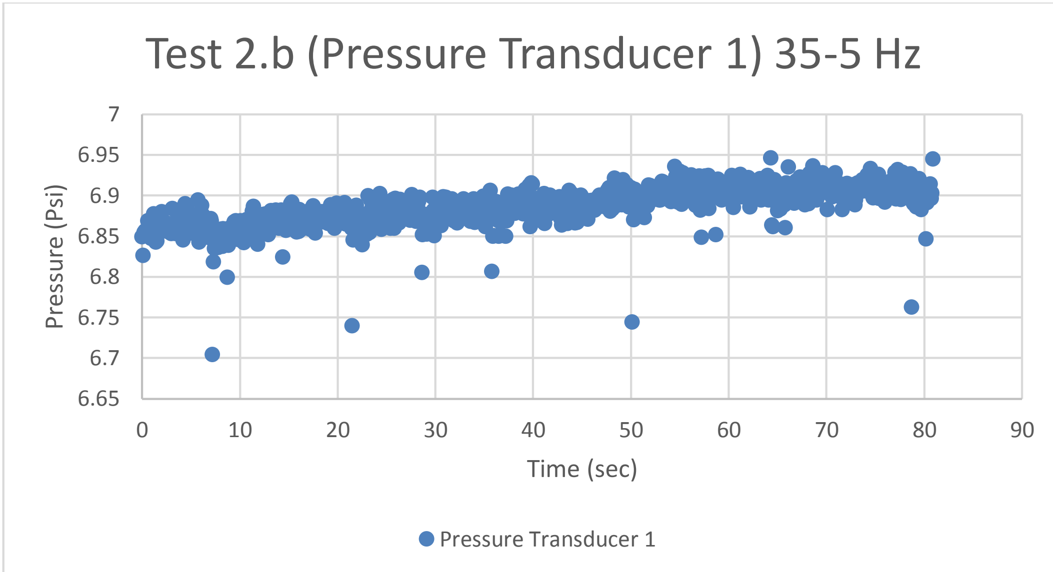

Fig. 23—Test 2.b. Pressure Data from Pressure Transducer 1

From **Fig. 23**, the pressure data increases as the air enters the system. The pressure increase is minimal when the overall pressure is taken into consideration. However the fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 17.5 ft. and the bubble migration continued through the riser.

4.2.3. Test 2.c Results- 35-10 Hz Pump Frequencies

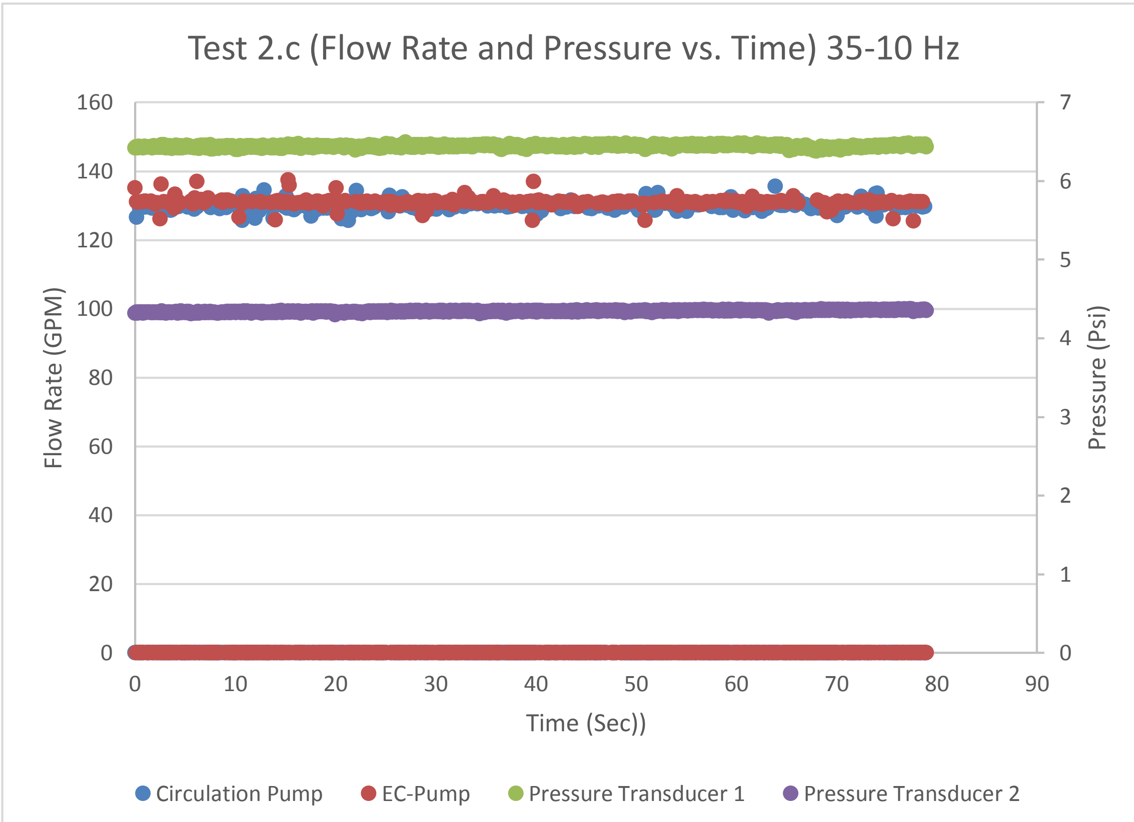

Fig. 24—Test 2.c Circulation and Ec-Pump Rates and Pressure vs Time @ 35-10 Hz Pump Rates

As seen in **Fig. 24**, the circulation pump and EC-Pump were maintained at an average rate of 132.2 GPM and 131.6 GPM respectively. The pressure at the base of the riser simulator was stable at 6.44 psi. The graph below shows a closer look at the pressure data acquired from this test.

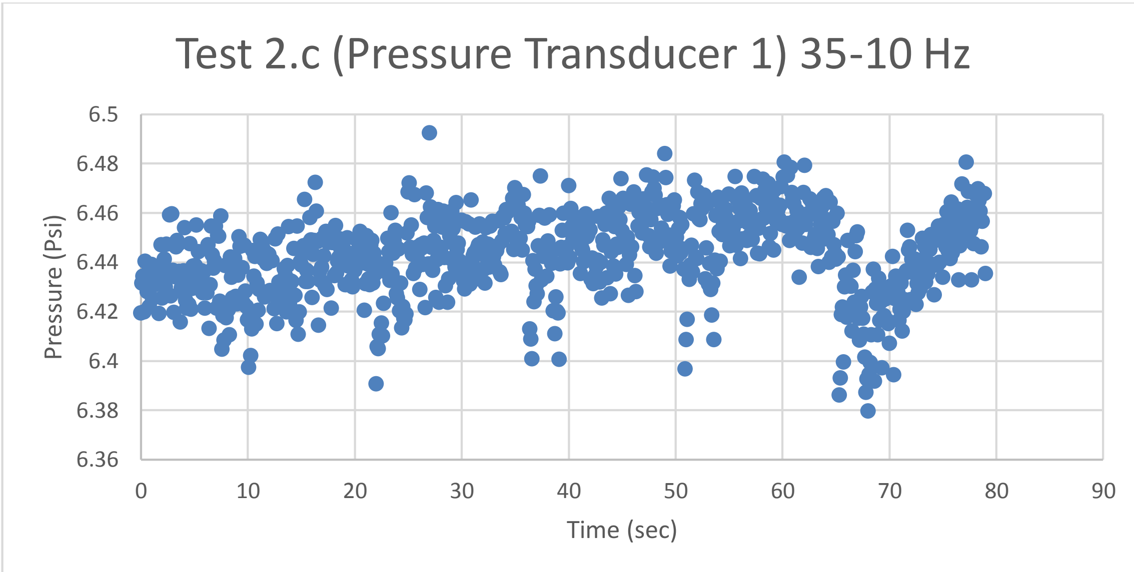

Fig. 25—Test 2.c Pressure Data from Pressure Transducer 1

From **Fig. 25**, the pressure data increases as the air enters the system. The pressure increase is minimal when the overall pressure is taken into consideration. However the fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 17 ft. and the bubble migration continued through the riser. However the bubble migration velocity was observed to be slower than the previous tests with less bubble traveling up the riser.

4.2.4. Test 2.d Results- 35-15 Hz Pump Frequencies

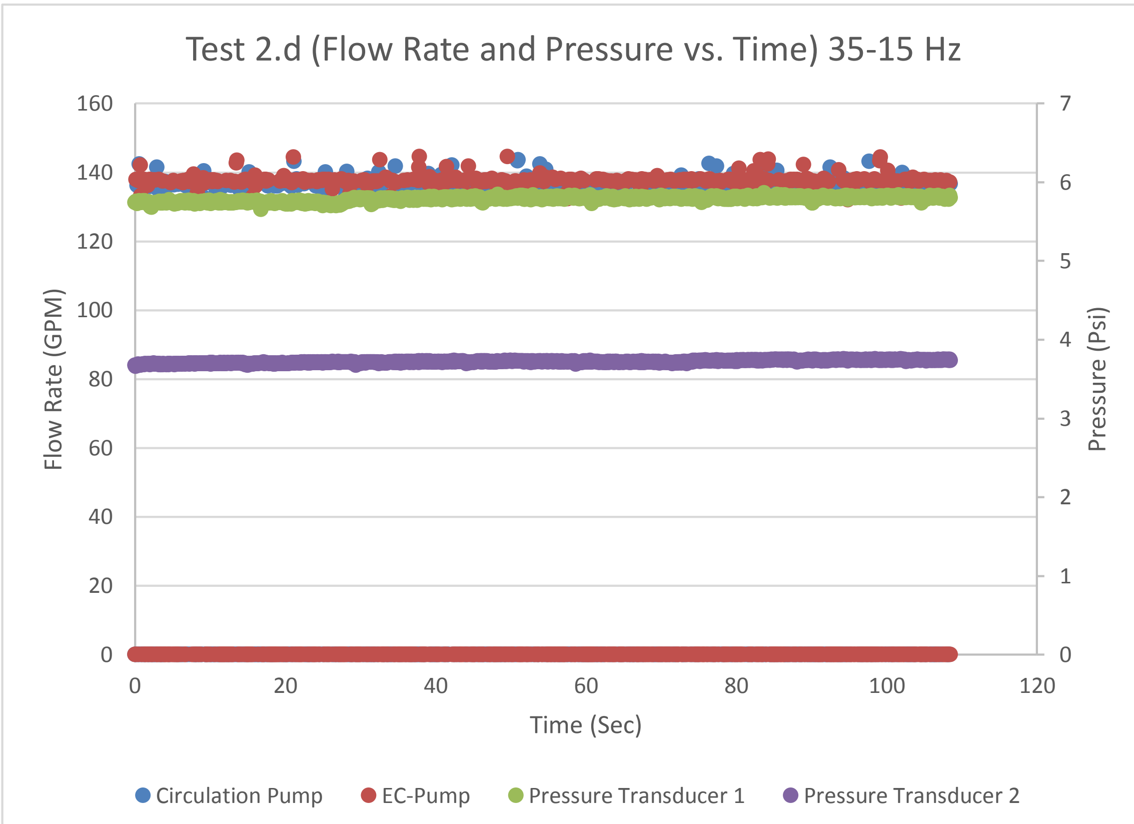

Fig. 26—Test 2.d Circulation and Ec-Pump Rates and Pressure vs Time @ 35-15 Hz Pump Rates

As seen in **Fig. 26**, the circulation pump and EC-Pump were maintained at an average rate of 139.5 GPM and 138.7 GPM respectively. The pressure at the base of the riser simulator was stable at 5.79 psi. The graph below shows a closer look at the pressure data acquired from this test.

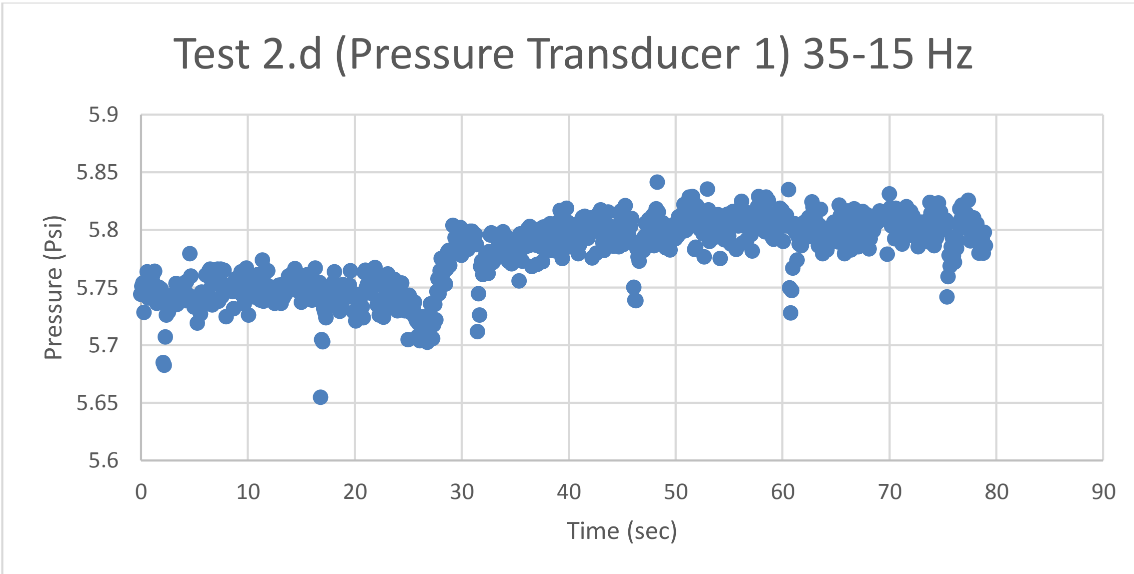

Fig. 27—Test 2.d. Pressure Data from Pressure Transducer 1

From **Fig. 27**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.1 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 15.5 ft. and the bubble migration continued through the riser. However the bubble migration velocity was observed to be slower than the previous tests with less bubble traveling up the riser. The bubble size was reduced with this EC-Pump Flow Rate.

4.2.5. Test 2.e Results- 35-20 Hz Pump Frequencies

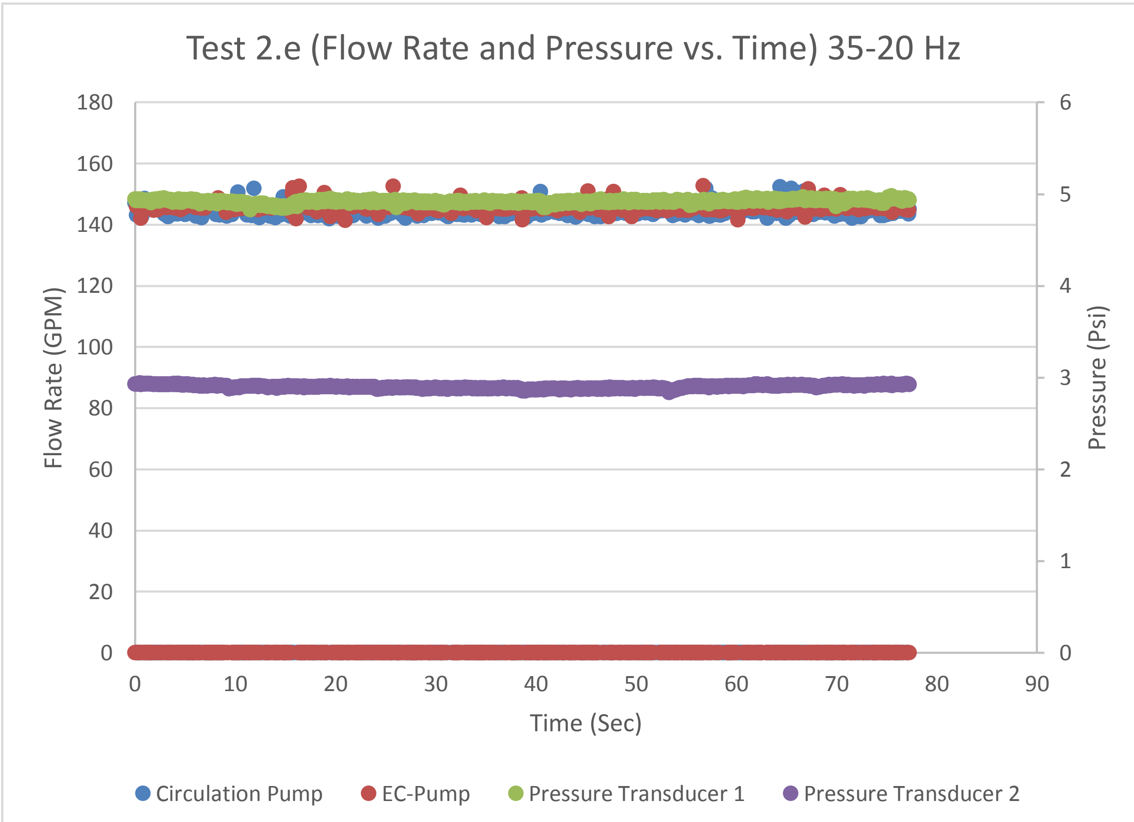

Fig. 28—Test 2.e Circulation and Ec-Pump Rates and Pressure vs Time @ 35-20 Hz Pump Rates

As seen in **Fig. 28,** the circulation pump and EC-Pump were maintained at an average rate of 148.6 GPM and 147.8 GPM respectively. The pressure at the base of the riser simulator was stable at 4.92 psi. The graph below shows a closer look at the pressure data acquired from this test.

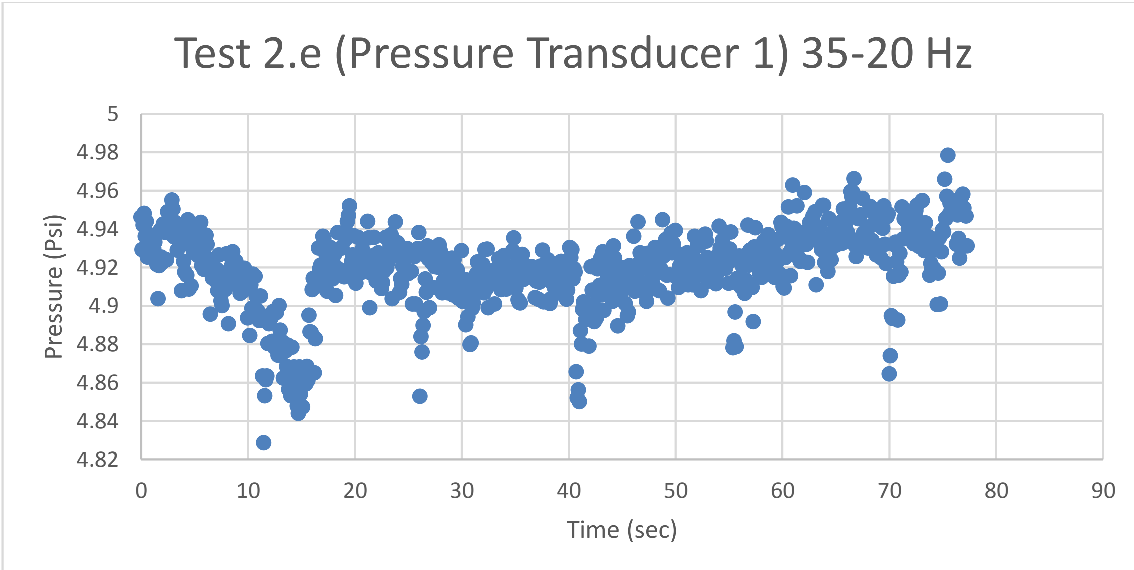

Fig. 29—Test 2.e. Pressure Data from Pressure Transducer 1

From **Fig. 29**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.15 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 14.5 ft. and the bubble migration continued through the riser. However the bubble migration velocity was observed to be slower than the previous tests with less bubble traveling up the riser. The bubble size was reduced with this EC-Pump Flow Rate.

4.3. Test Set #3: Full Vertical Test with 37.5 Hz Circulation Frequency

4.3.1. Test 3.a. Results- 37.5-10 Hz Pump Frequencies

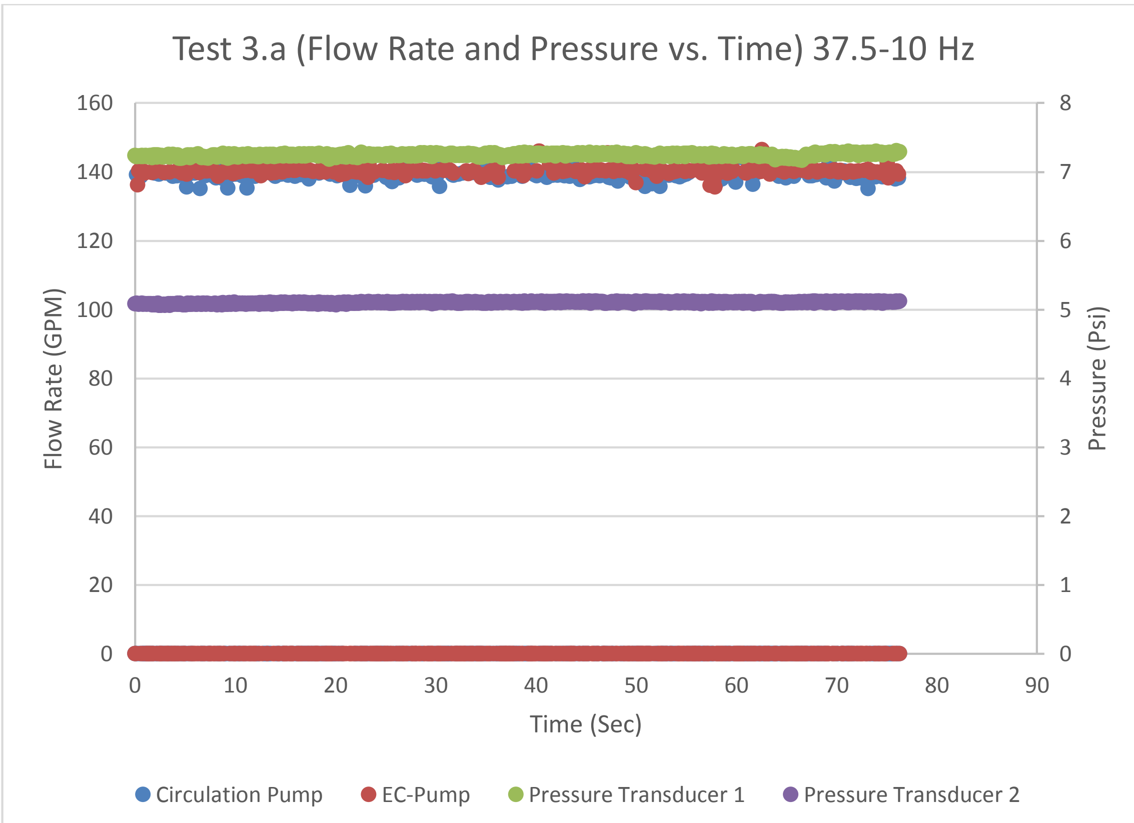

Fig. 30—Test 3.a Circulation and Ec-Pump Rates and Pressure vs Time @ 37.5-10 Hz Pump Rates

As seen in **Fig. 30**, the circulation pump and EC-Pump were maintained at an average rate of 142 GPM and 142.4 GPM respectively. The pressure at the base of the riser simulator was stable at 7.24 psi. The graph below shows a closer look at the pressure data acquired from this test.

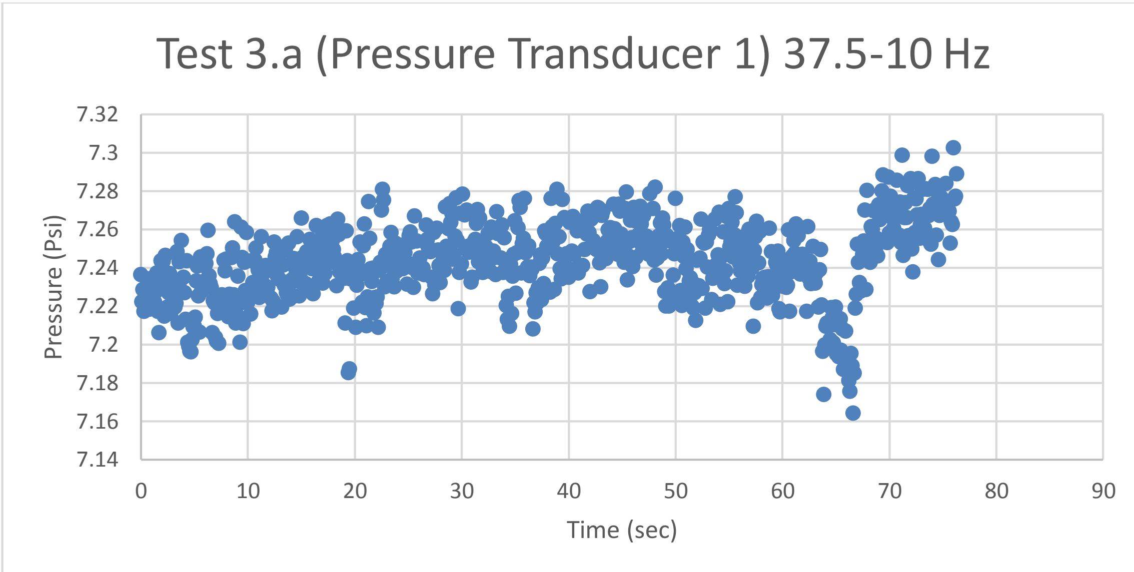

Fig. 31—Test 3.a. Pressure Data from Pressure Transducer 1

From **Fig. 31**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.15 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 18 ft. and the bubble migration continued through the riser.

4.3.2. Test 3.b. Results- 37.5-15 Hz Pump Frequencies

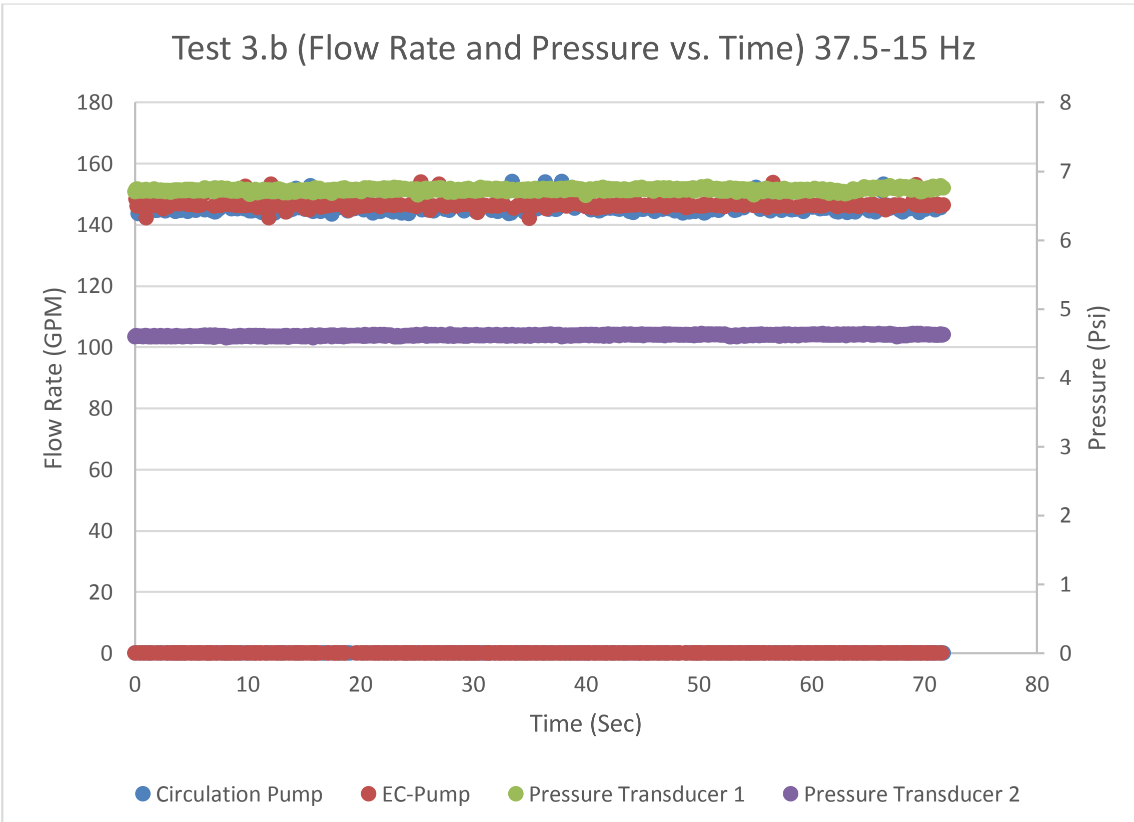

Fig. 32—Test 3.b Circulation and Ec-Pump Rates and Pressure vs Time @ 37.5-15 Hz Pump Rates

As seen in **Fig. 32**, the circulation pump and EC-Pump were maintained at an average rate of 151 GPM and 149.3 GPM respectively. The pressure at the base of the riser simulator was stable at 6.73 psi. The graph below shows a closer look at the pressure data acquired from this test.

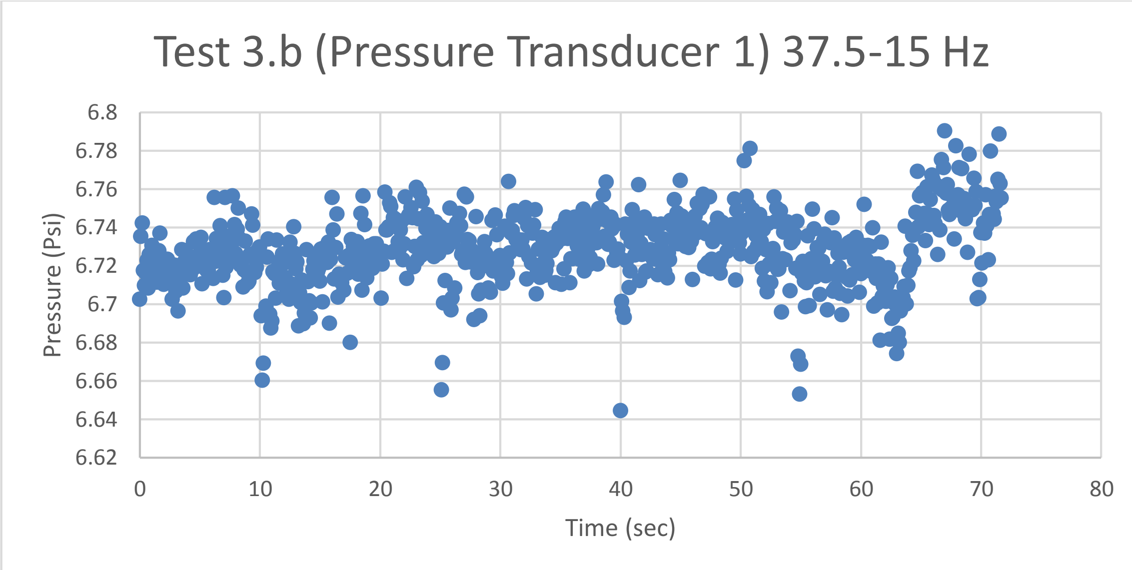

Fig. 33—Test 3.b. Pressure Data from Pressure Transducer 1

From **Fig. 33**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.15 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 17.5 ft. and the bubble migration continued through the riser. However the bubble migration velocity was observed to be slower than the previous tests with less bubble traveling up the riser. The bubble size was reduced with this EC-Pump Flow Rate. It was observed that an air trap was created at the EC-Drill™ Outlet from the riser causing a large bubble formation.

4.3.3. Test 3.c. Results- 37.5-20 Hz Pump Frequencies

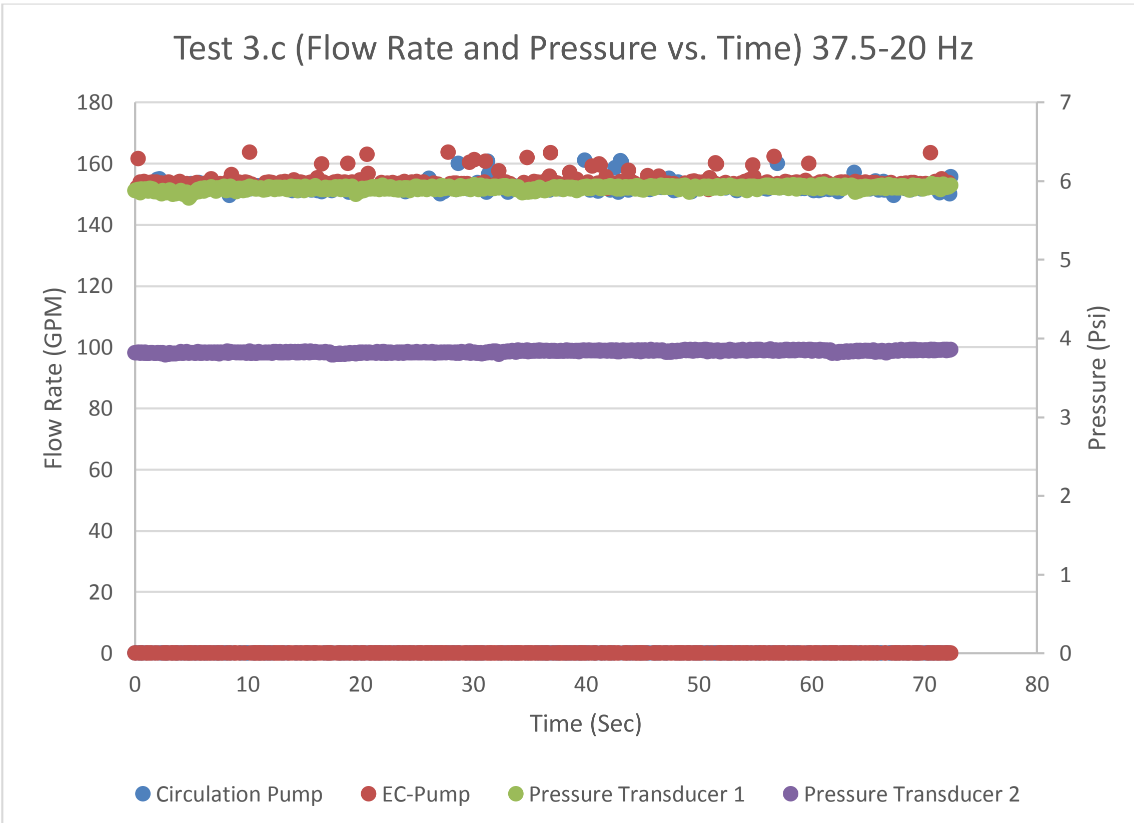

Fig. 34—Test 3.c Circulation and Ec-Pump Rates and Pressure vs Time @ 37.5-20 Hz Pump Rates

As seen in **Fig. 34**, the circulation pump and EC-Pump were maintained at an average rate of 157.3 GPM and 158 GPM respectively. The pressure at the base of the riser simulator was stable at 5.91 psi. The graph below shows a closer look at the pressure data acquired from this test.

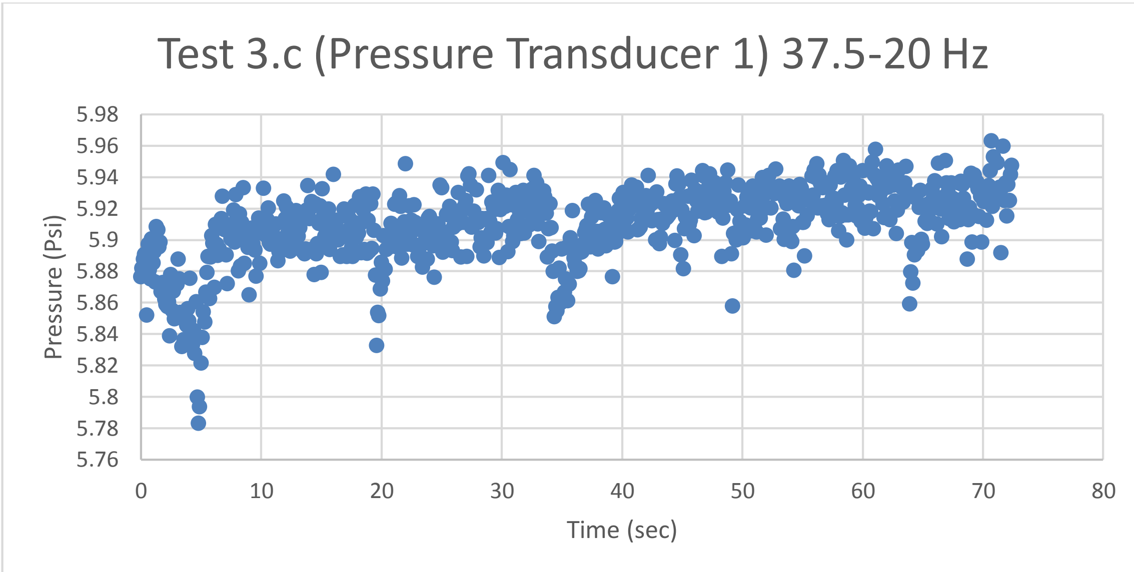

Fig. 35—Test 3.c. Pressure Data from Pressure Transducer 1

From **Fig. 35**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.17 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 15.5 ft. and the bubble migration continued through the riser. However the bubble migration velocity was observed to be slower than the previous tests with less bubble traveling up the riser. The bubble size was reduced with this EC-Pump Flow Rate. The air trap continued to produce large bubbles however most of the air exited the system at the EC-Pump.

4.3.4. Test 3.d. Results- 37.5-25 Hz Pump Frequencies

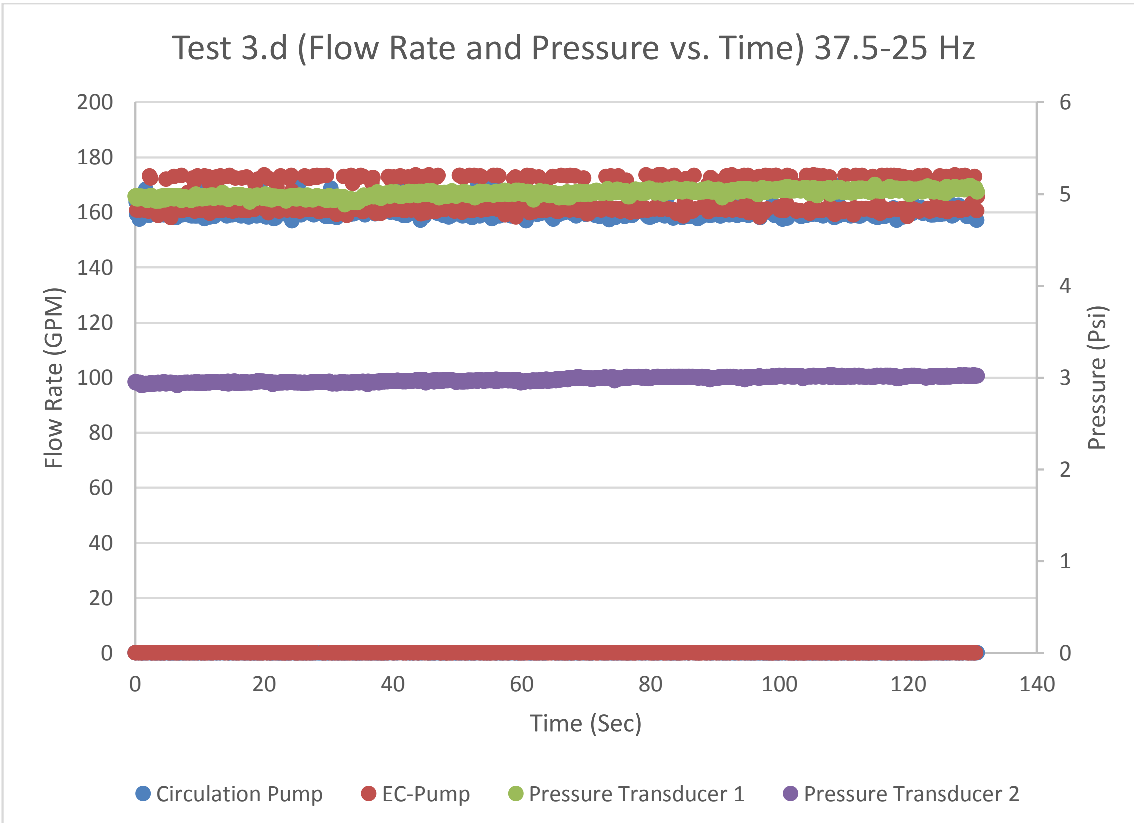

Fig. 36—Test 3.d Circulation and Ec-Pump Rates and Pressure vs Time @ 37.5-25 Hz Pump Rates

As seen in **Fig. 36**, the circulation pump and EC-Pump were maintained at an average rate of 165.2 GPM and 165.7 GPM respectively. The pressure at the base of the riser simulator was stable at 5 psi. The graph below shows a closer look at the pressure data acquired from this test.

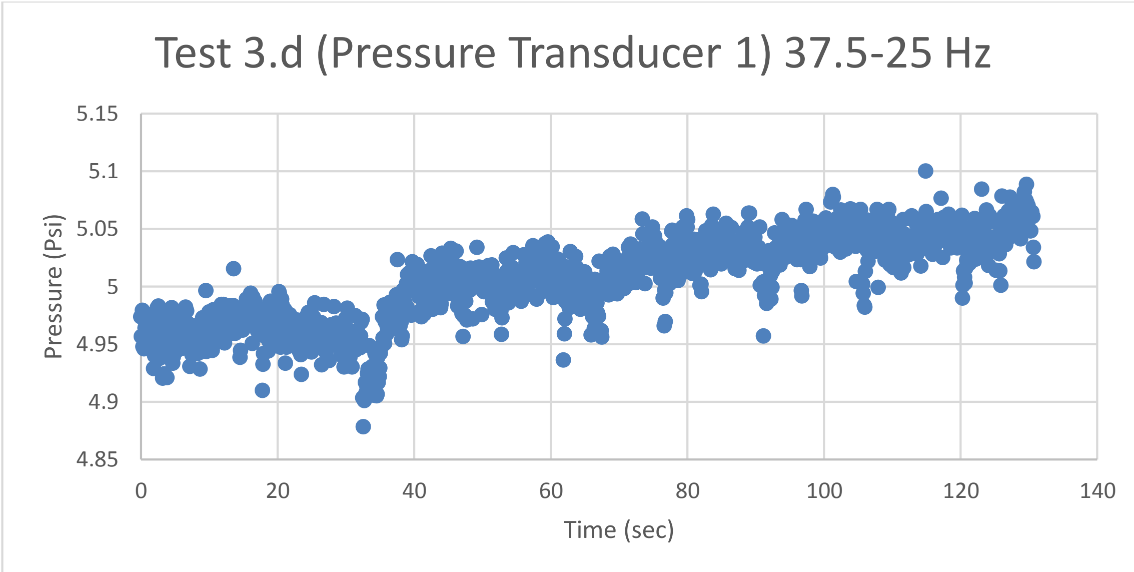

Fig. 37—Test 3.d. Pressure Data from Pressure Transducer 1

From **Fig. 37**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.35 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 13.5 ft. and the bubble migration continued through the riser. However the bubble migration velocity was observed to be slower than the previous tests with less bubble traveling up the riser. It was observed that an air trap was created at the EC-Drill™ Outlet from the riser causing a large bubble formation. The bubble size was greatly reduced.

4.4. Test Set #4: Full Vertical Test with 40 Hz Circulation Frequency

4.4.1. Test 4.a. Results- 40-7.5 Hz Pump Frequencies

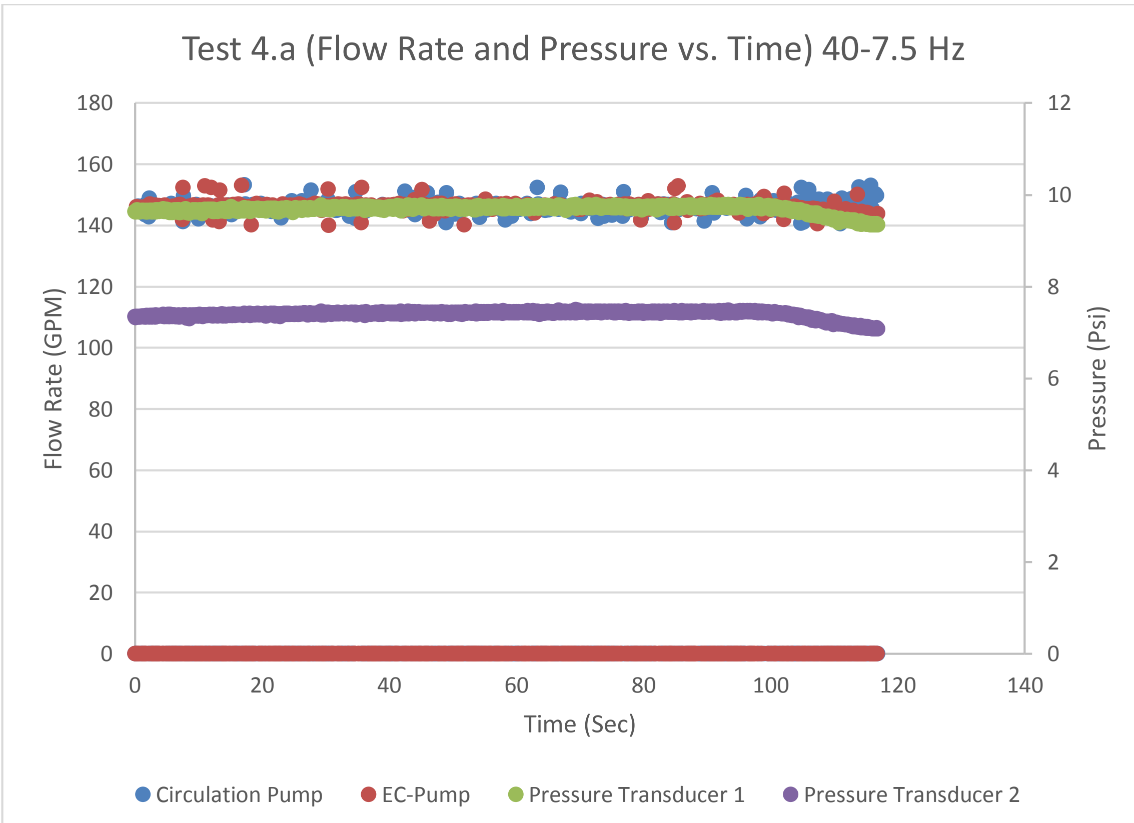

Fig. 38—Test 4.a Circulation and Ec-Pump Rates and Pressure vs Time @ 40-7.5 Hz Pump Rates

As seen in **Fig. 38**, the circulation pump and EC-Pump were maintained at an average rate of 147.2 GPM and 147 GPM respectively. The pressure at the base of the riser simulator was stable at 9.7 psi. The graph below shows a closer look at the pressure data acquired from this test.

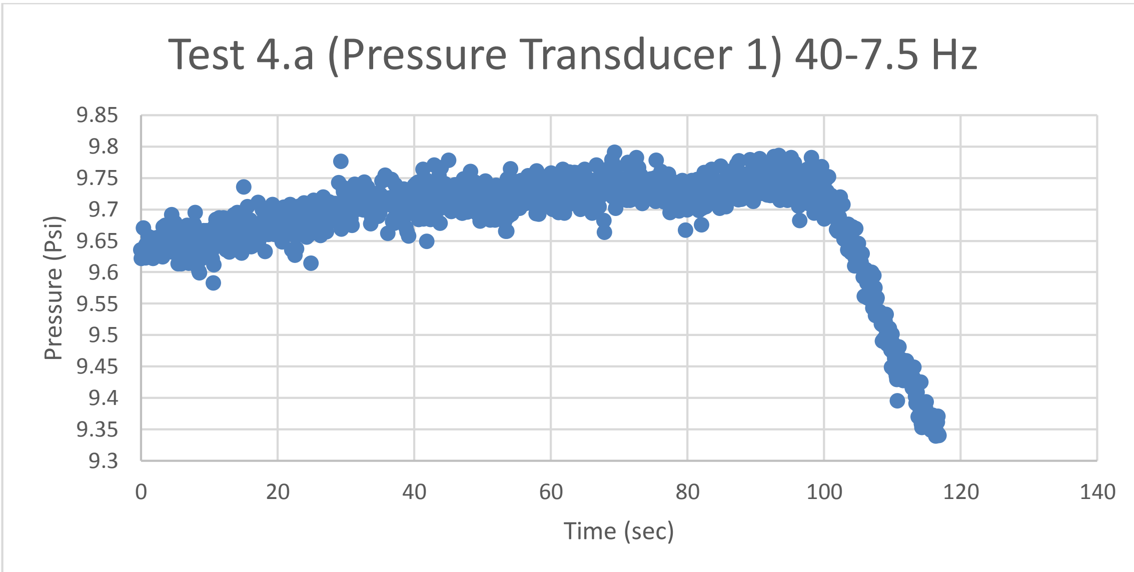

Fig. 39—Test 4.a. Pressure Data from Pressure Transducer 1

From **Fig. 39**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.42 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 24 ft. and the bubble migration continued through the riser. Larger bubble formation continued with the air trap located at the EC-Pump exit. However with the high Circulation rate the bubble size at the base was greatly reduced and dispersed.

4.4.2. Test 4.b. Results- 40-10 Hz Pump Frequencies

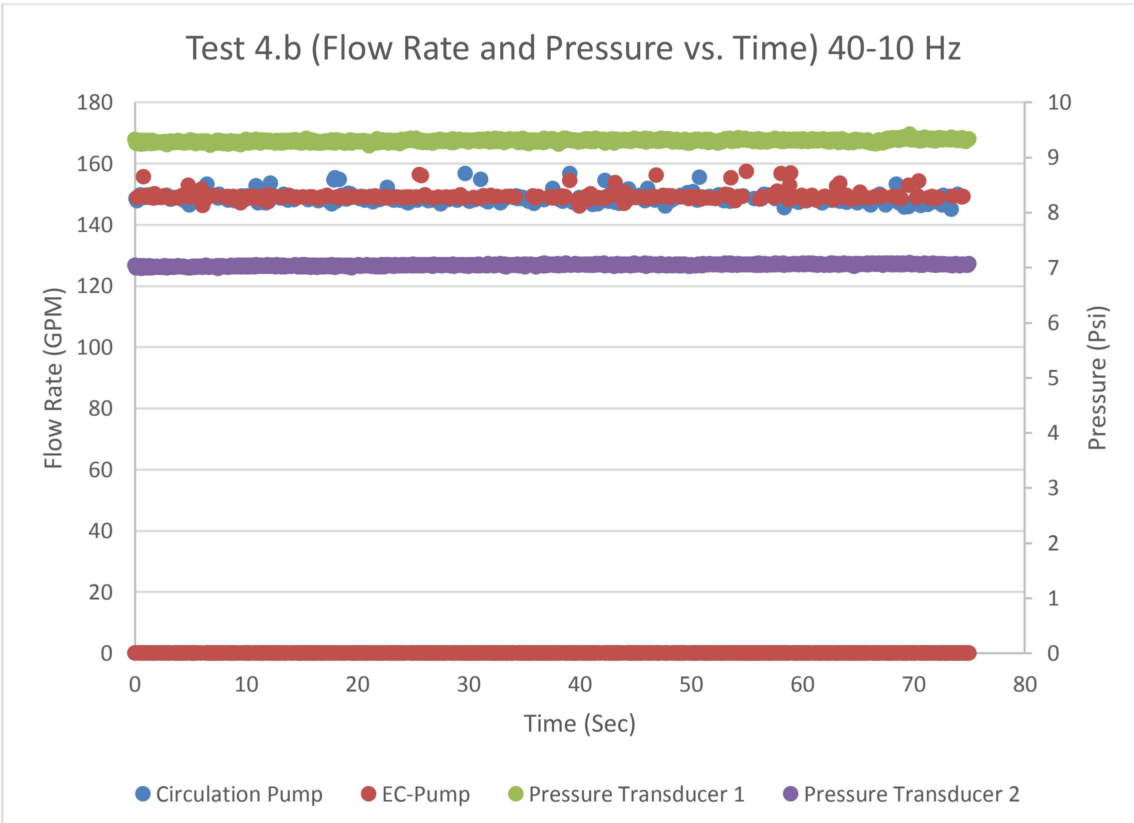

Fig. 40—Test 4.b Circulation and Ec-Pump Rates and Pressure vs Time @ 40-10 Hz Pump Rates

As seen in **Fig. 40**, the circulation pump and EC-Pump were maintained at an average rate of 152.5 GPM and 152.8 GPM respectively. The pressure at the base of the riser simulator was stable at 9.3 psi. The graph below shows a closer look at the pressure data acquired from this test.

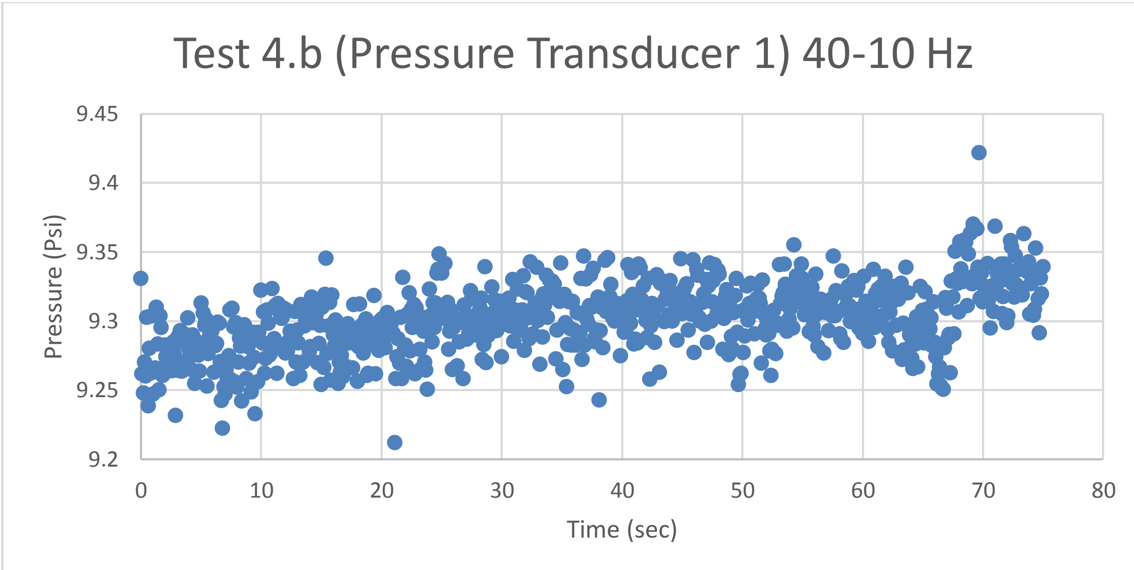

Fig. 41—Test 4.b. Pressure Data from Pressure Transducer 1

From **Fig. 41**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.15 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 23 ft. and the bubble migration continued through the riser. Larger bubble formation continued with the air trap located at the EC-Pump exit. The high Circulation rate the bubble size at the base was greatly reduced and dispersed.

4.4.3. Test 4.c. Results- 40-12.5 Hz Pump Frequencies

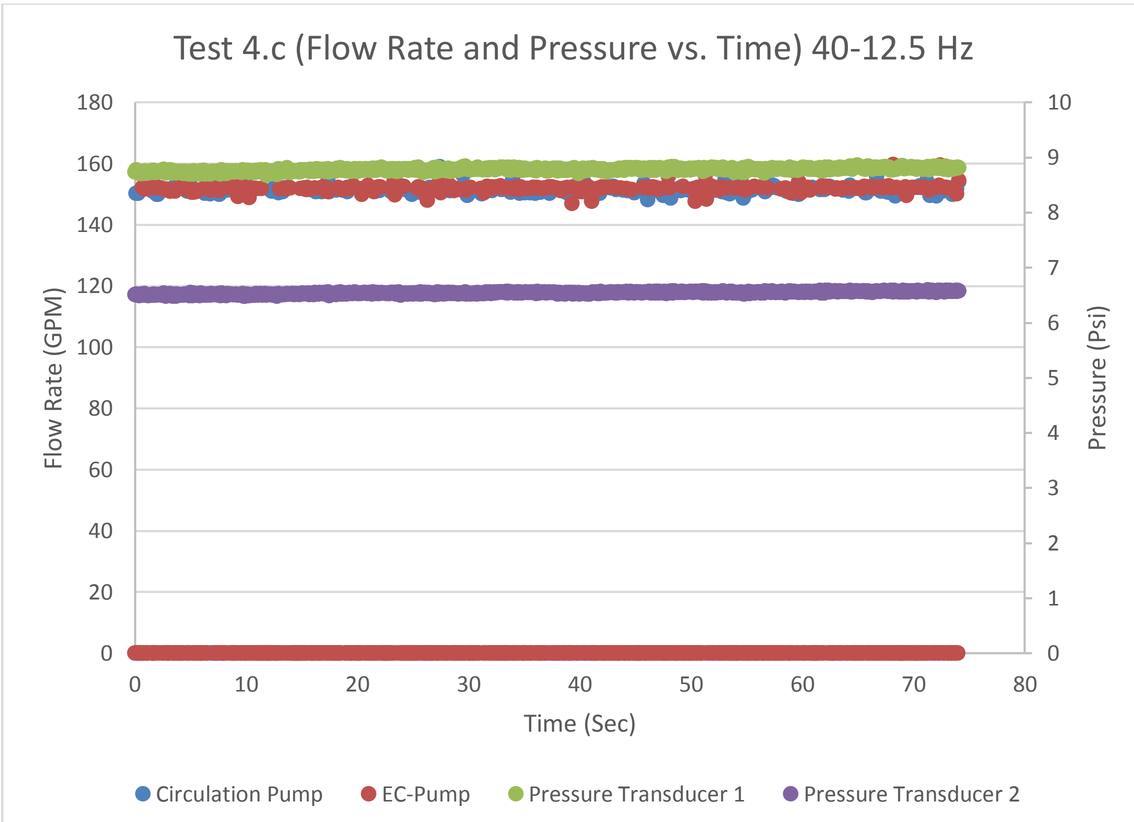

Fig. 42—Test 4.c Circulation and Ec-Pump Rates and Pressure vs Time @ 40-12.5 Hz Pump Rates

As seen in **Fig. 42**, the circulation pump and EC-Pump were maintained at an average rate of 155.7 GPM and 154.1 GPM respectively. The pressure at the base of the riser simulator was stable at 8.78 psi. The graph below shows a closer look at the pressure data acquired from this test.

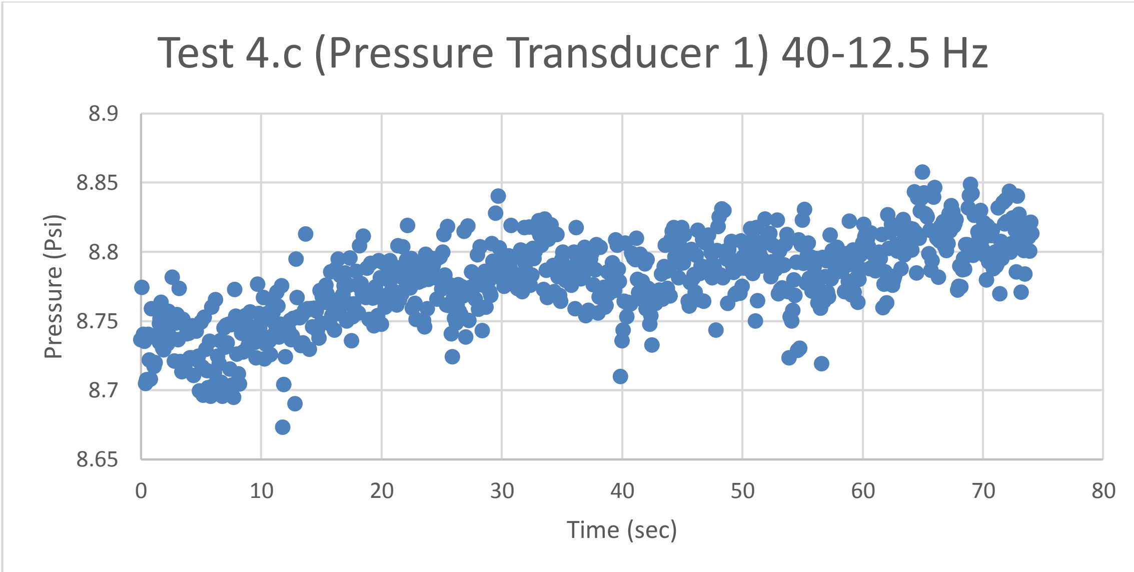

Fig. 43—Test 4.c. Pressure Data from Pressure Transducer 1

From **Fig. 43**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.20 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 22.5 ft. and the bubble migration continued through the riser. Larger bubble formation continued with the air trap located at the EC-Pump exit. With the high Circulation rate the bubble size at the base was greatly reduced and dispersed. The higher EC-Pump rate and the reduced bubble size restricted the migration velocity, which allowed an increase in the diverted gas bubble.

4.4.4. Test 4.d. Results- 40-15 Hz Pump Frequencies

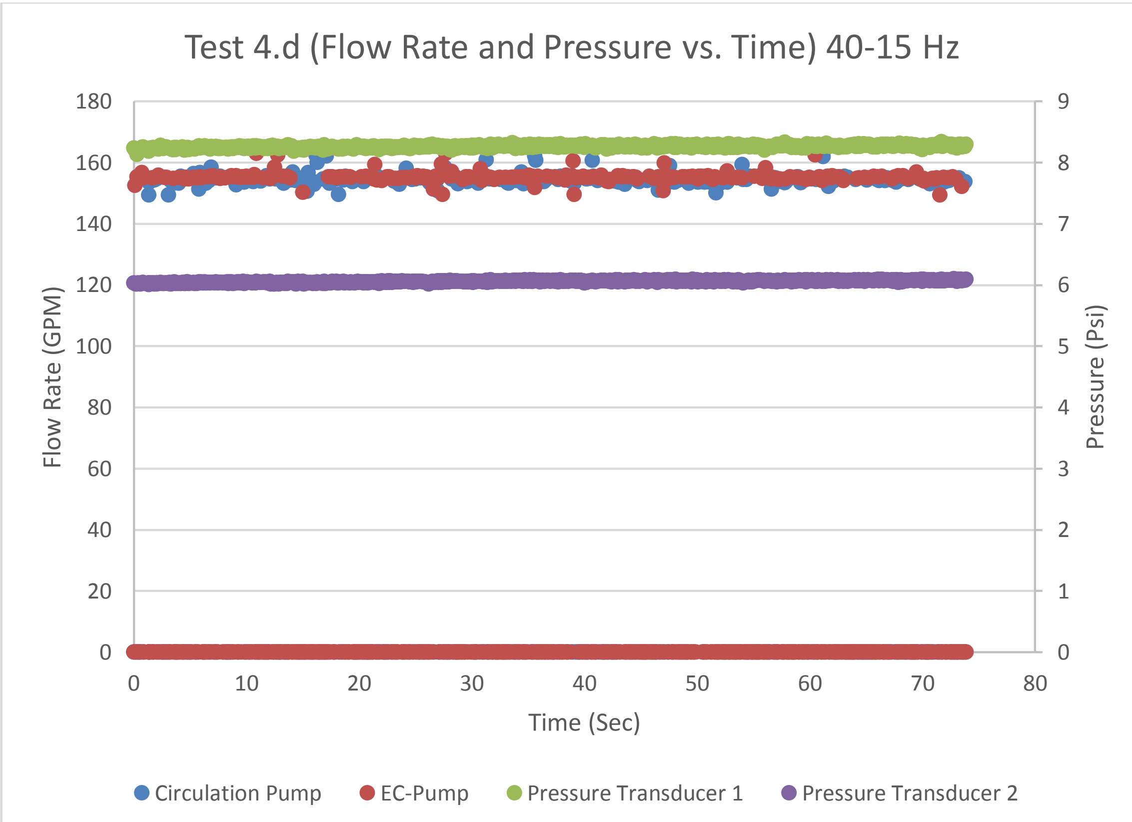

Fig. 44—Test 4.d Circulation and Ec-Pump Rates and Pressure vs Time @ 40-15 Hz Pump Rates

As seen in **Fig. 44**, the circulation pump and EC-Pump were maintained at an average rate of 157 GPM and 157.1 GPM respectively. The pressure at the base of the riser simulator was stable at 8.27 psi. The graph below shows a closer look at the pressure data acquired from this test.

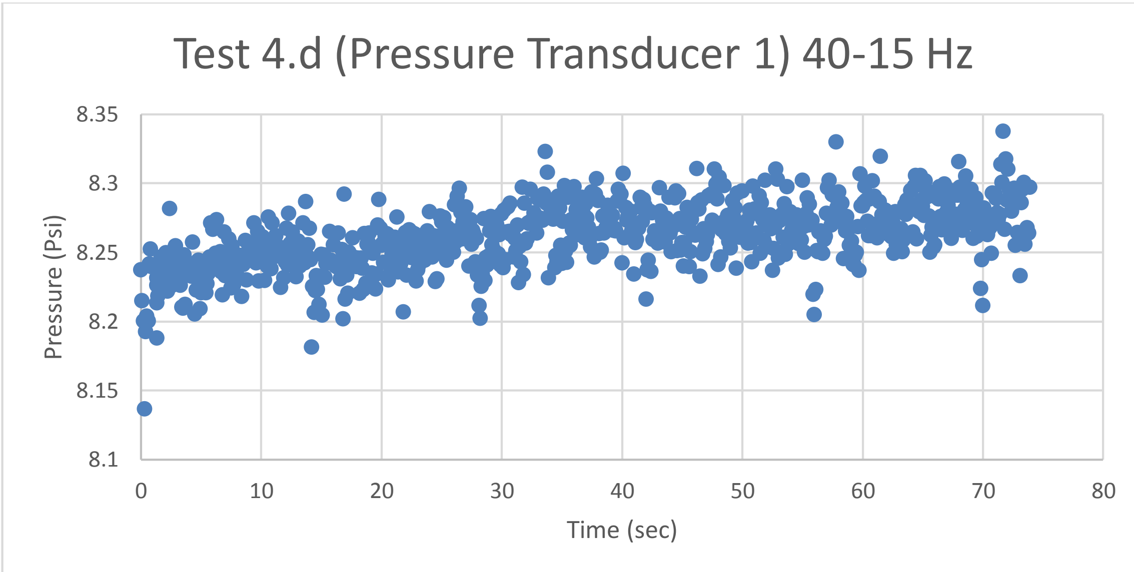

Fig. 45—Test 4.d. Pressure Data from Pressure Transducer 1

From **Fig. 45**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.20 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 21 ft. and the bubble migration continued through the riser. Larger bubble formation continued with the air trap located at the EC-Pump exit. With the high Circulation rate the bubble size at the base was greatly reduced and dispersed. The higher EC-Pump rate and the reduced bubble size restricted the migration velocity, which allowed an increase in the diverted gas bubble.

4.4.5. Test 4.e. Results- 40-17.5 Hz Pump Frequencies

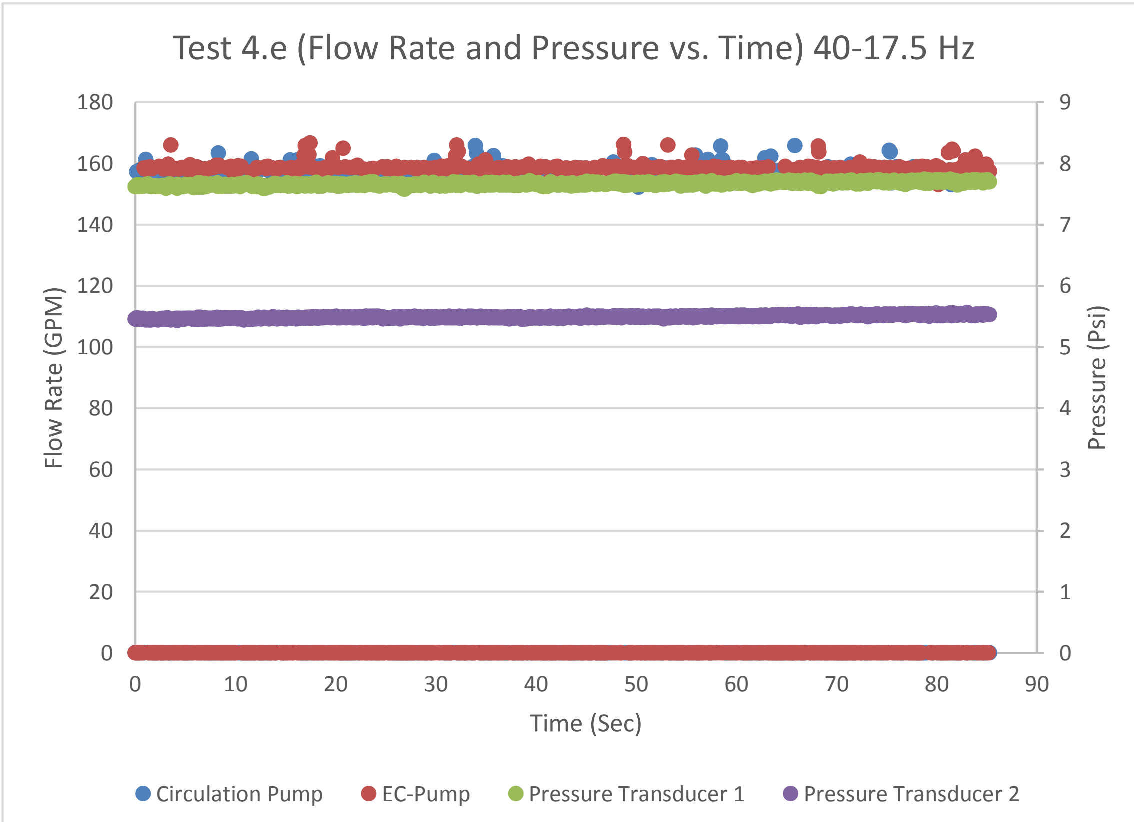

Fig. 46—Test 4.e Circulation and Ec-Pump Rates and Pressure vs Time @ 40-17.5 Hz Pump Rates

As seen in **Fig. 46**, the circulation pump and EC-Pump were maintained at an average rate of 160.1 GPM and 161.1 GPM respectively. The pressure at the base of the riser simulator was stable at 7.66 psi. The graph below shows a closer look at the pressure data acquired from this test.

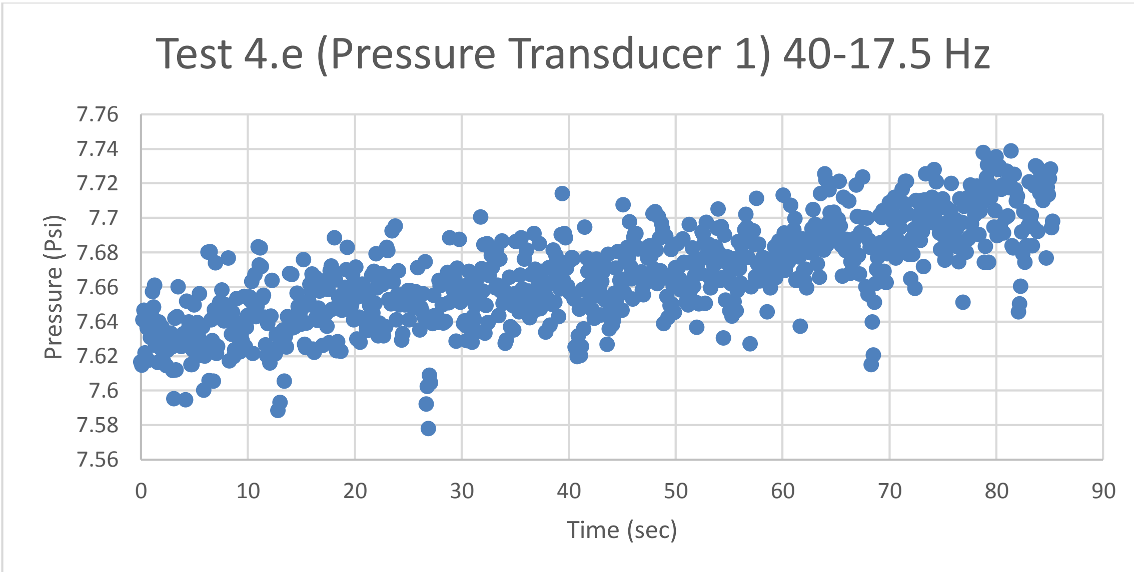

Fig. 47—Test 4.e. Pressure Data from Pressure Transducer 1

From **Fig. 47**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.18 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 19 ft. and with the high circulation and EC-Pump rate the bubble migration through the riser reduced significantly and the migration velocity was also reduced.

4.4.6. Test 4.f. Results- 40-20 Hz Pump Frequencies

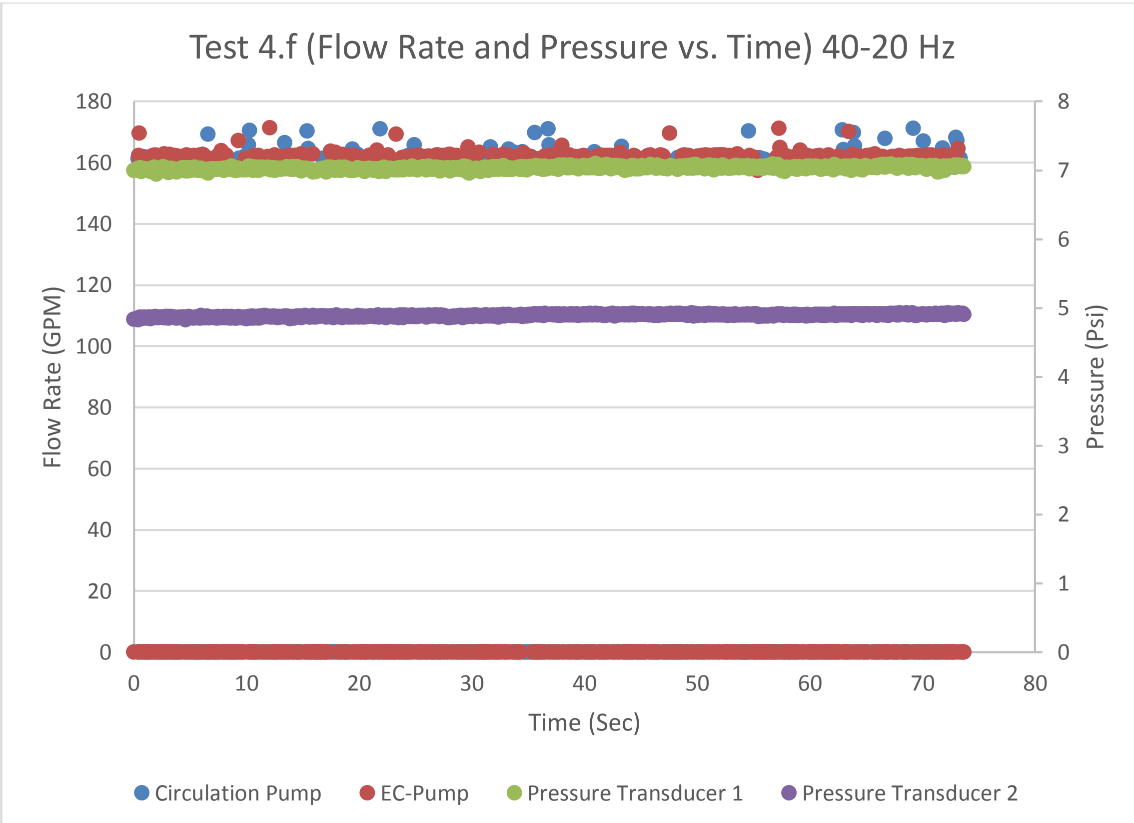

Fig. 48—Test 4.f Circulation and Ec-Pump Rates and Pressure vs Time @ 40-20 Hz Pump Rates

As seen in **Fig. 48**, the circulation pump and EC-Pump were maintained at an average rate of 165.9 GPM and 165.7 GPM respectively. The pressure at the base of the riser simulator was stable at 7.03 psi. The graph below shows a closer look at the pressure data acquired from this test.

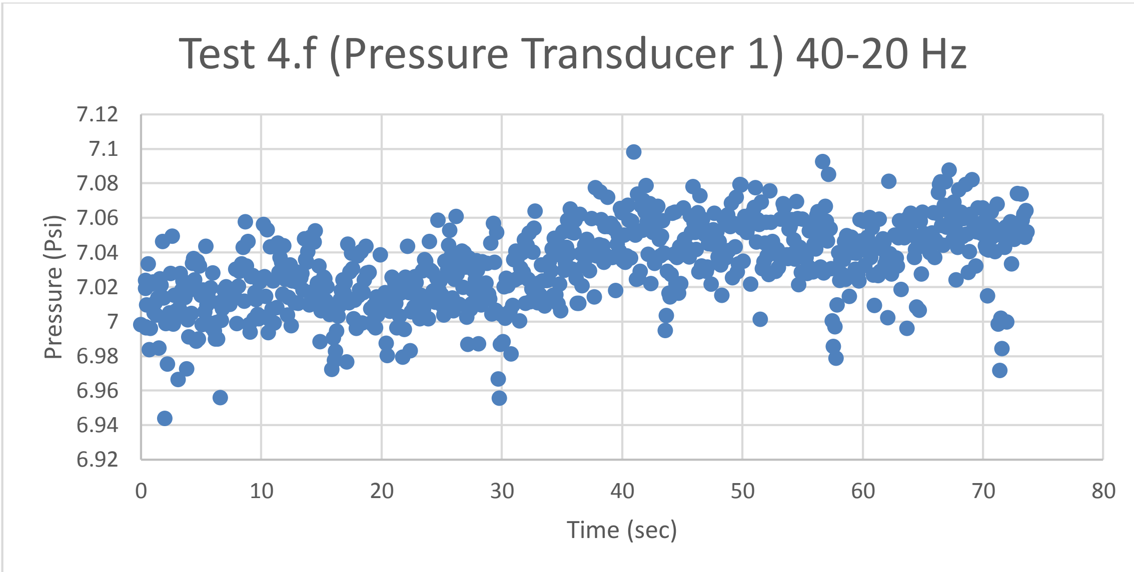

Fig. 49—Test 4.f. Pressure Data from Pressure Transducer 1

From **Fig. 49**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.15 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 18 ft. and with the high circulation and EC-Pump rate the bubble migration through the riser reduced significantly and the migration velocity was also reduced.

4.4.7. Test 4.g. Results- 40-22.5 Hz Pump Frequencies

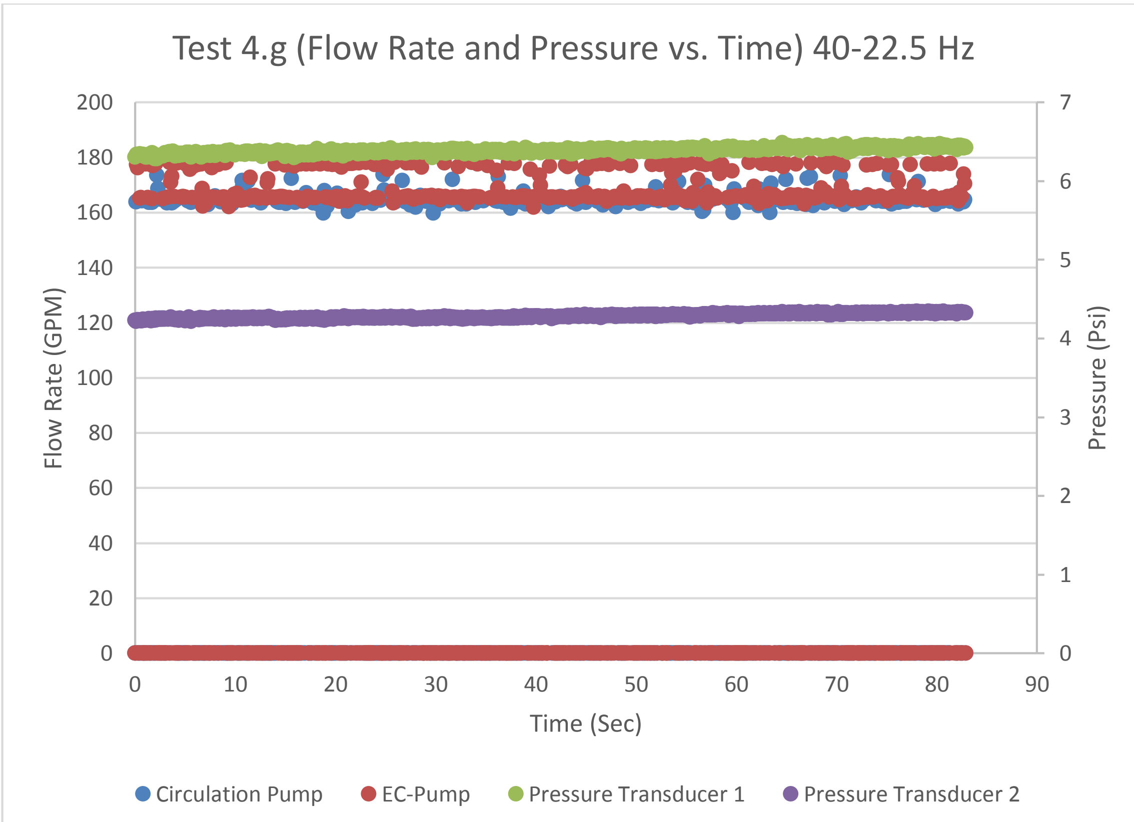

Fig. 50—Test 4.g Circulation and Ec-Pump Rates and Pressure vs Time @ 40-22.5 Hz Pump Rates

As seen in **Fig. 50**, the circulation pump and EC-Pump were maintained at an average rate of 168.2 GPM and 170.4 GPM respectively. The pressure at the base of the riser simulator was stable at 6.4 psi. The graph below shows a closer look at the pressure data acquired from this test.

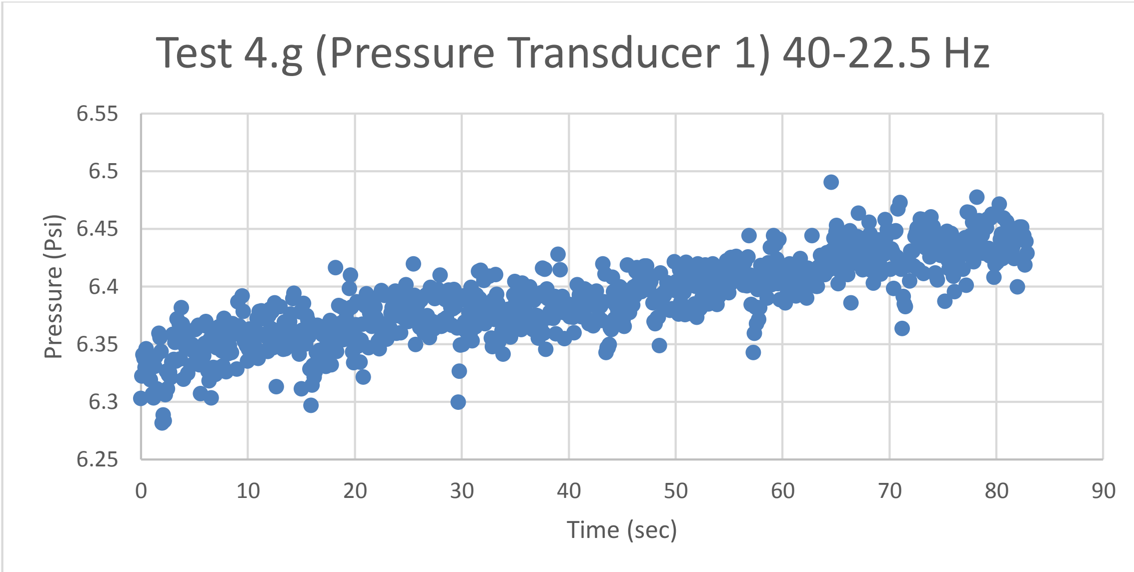

Fig. 51—Test 4.g. Pressure Data from Pressure Transducer 1

From **Fig. 51**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.22 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 16.5 ft. and with the high circulation and EC-Pump rate the bubble migration through the riser reduced significantly and the migration velocity was also reduced. With these flow rates most of the gas exited the system at the EC-Pump, however the airgap continued to create large bubbles once there was enough gas accumulation at the EC-Pump Tee.

4.4.8. Test 4.h. Results- 40-25 Hz Pump Frequencies

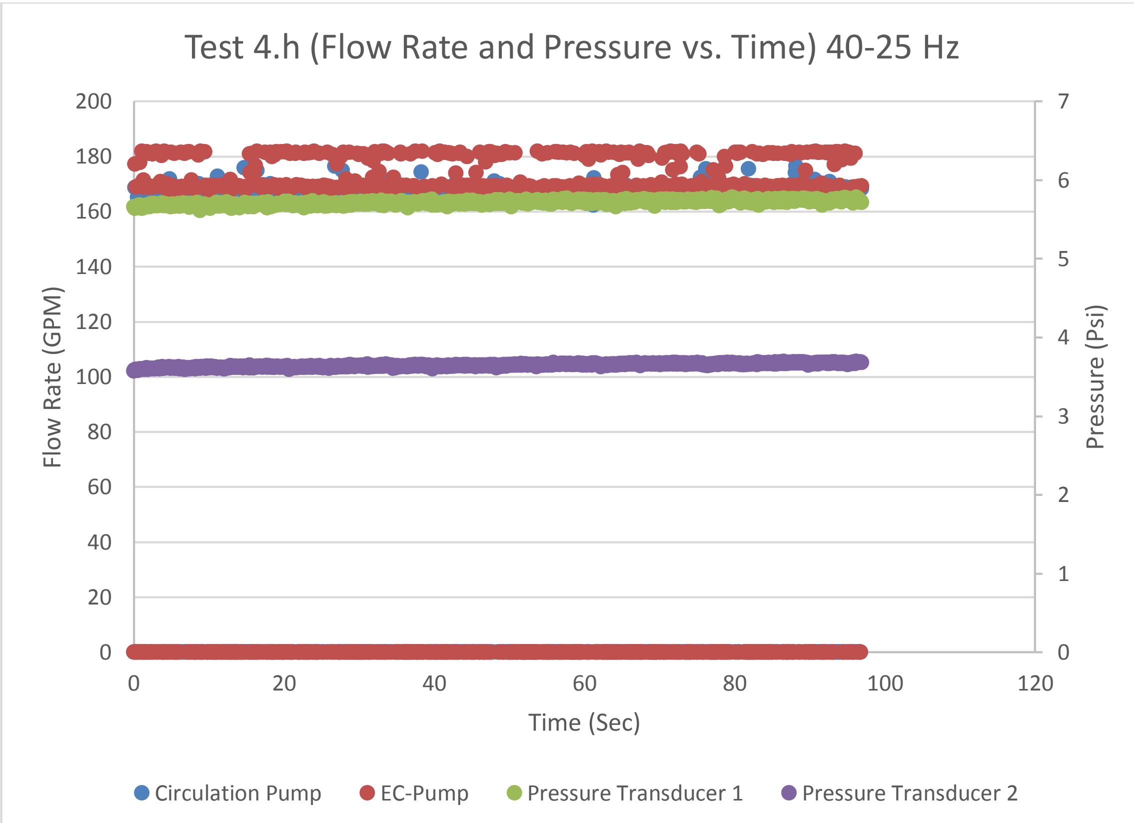

Fig. 52—Test 4.h Circulation and Ec-Pump Rates and Pressure vs Time @ 40-25 Hz Pump Rates

As seen in **Fig. 52**, the circulation pump and EC-Pump were maintained at an average rate of 170.8 GPM and 173.5 GPM respectively. The pressure at the base of the riser simulator was stable at 5.7 psi. The graph below shows a closer look at the pressure data acquired from this test.

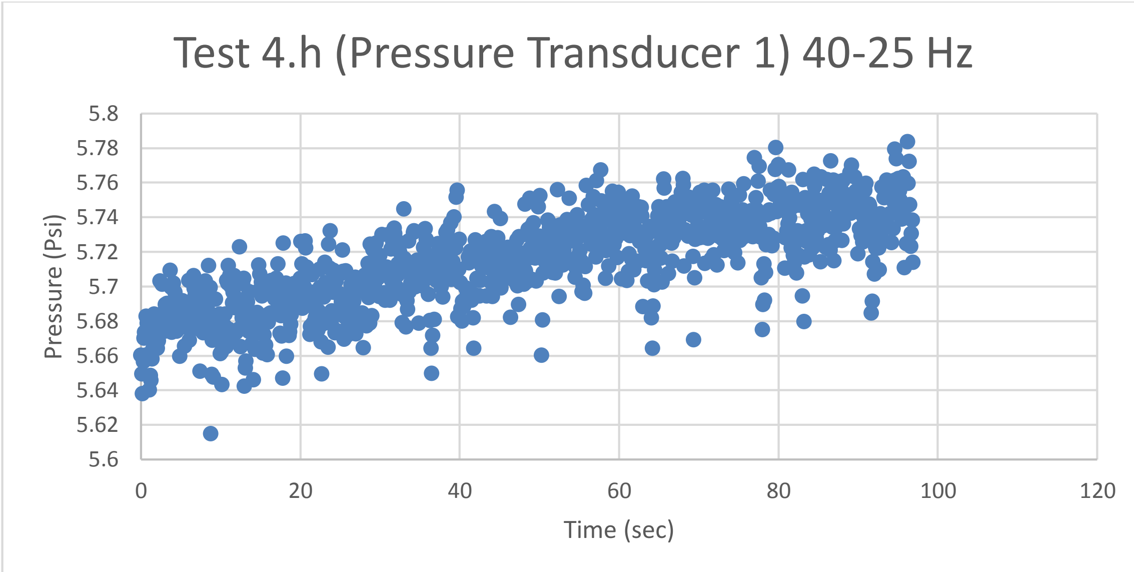

Fig. 53—Test 4.h. Pressure Data from Pressure Transducer 1

From **Fig. 53**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.17 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 15 ft. and with the high circulation and EC-Pump rate the bubble migration through the riser reduced significantly and the migration velocity was also reduced. With these flow rates most of the gas exited the system at the EC-Pump however the airgap continued to create large bubbles once there was enough gas accumulation at the EC-Pump Tee. Bubble size was greatly reduced.

4.4.9. Test 4.i. Results- 40-27.5 Hz Pump Frequencies

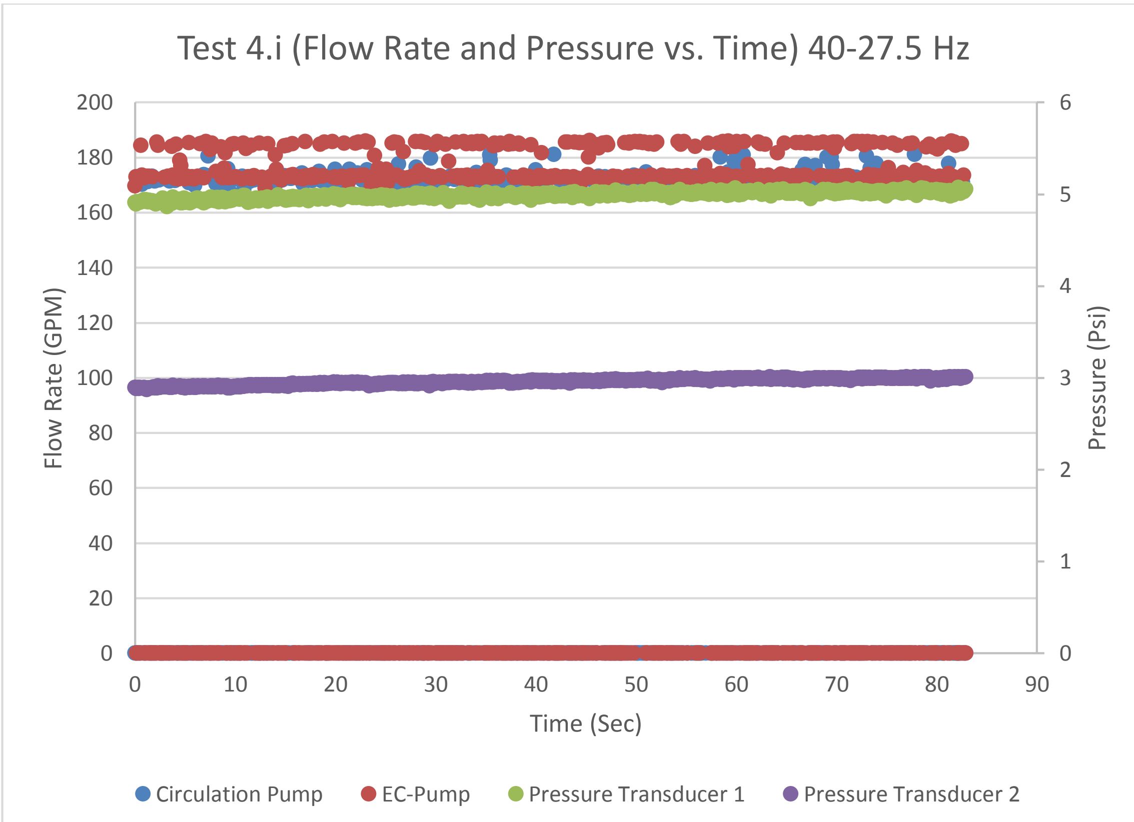

Fig. 54—Test 4.i Circulation and Ec-Pump Rates and Pressure vs Time @ 40-27.5 Hz Pump Rates

As seen in **Fig. 54**, the circulation pump and EC-Pump were maintained at an average rate of 174.7 GPM and 177.3 GPM respectively. The pressure at the base of the riser simulator was stable at 5 psi. The graph below shows a closer look at the pressure data acquired from this test.

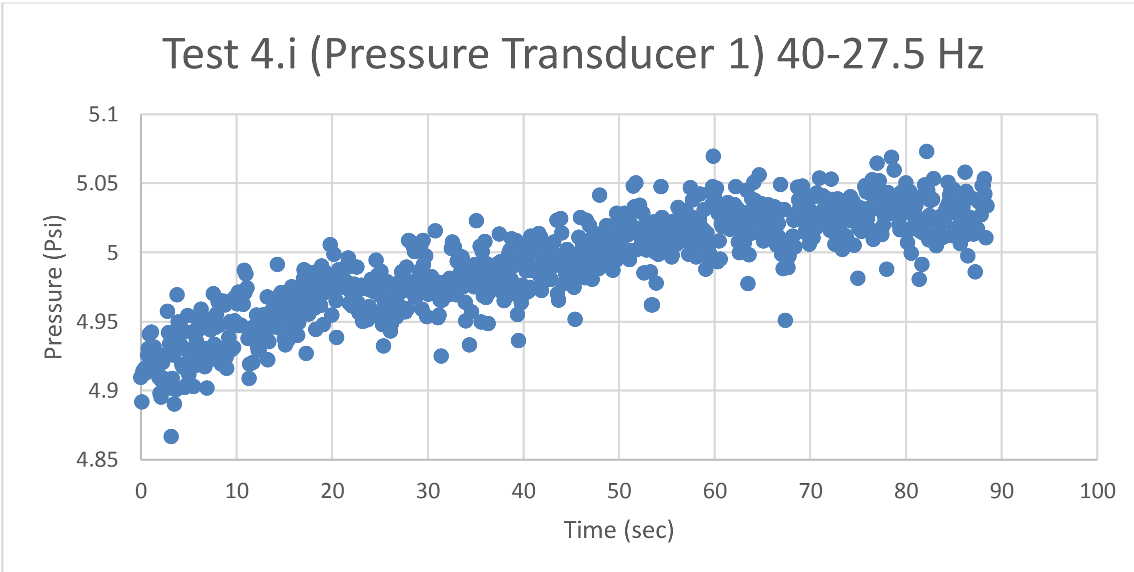

Fig. 55—Test 4.i. Pressure Data from Pressure Transducer 1

From **Fig. 55**, the pressure data increases as the air enters the system. The fluctuations also correspond to the issues faced with the centrifugal pumps that were used in the lab. The fluctuation in this test is about 0.21 psi. This issue can be seen in all of the data collected from the experiments.

The fluid level was maintained at 13.5 ft. and with the high circulation and EC-Pump rate the bubble migration through the riser reduced significantly and the migration velocity was also reduced. With these flow rates it was difficult to make a final conclusion on whether or not gas migrated in the riser. The air trap maintained a significance at the EC-Pump Tee and continued to create large gas bubbles which were released back in to the riser.

5. FUTURE WORK AND DEVELOPMENT

1. Upgrade pumps to allow for greater circulation rates which can also handle solids and viscous fluids to study equivalent lab scale flow velocities for comparison with field scale for circulation up to 2000 GPM.
2. Upgrade the liquid flow meters to improve precision and reduce error in the data. The upgraded flow meters should allow solids and viscous fluids.
3. Upgrading the pressure transducers, purchasing higher precision and sensitivity transducers will allow a better pressure profile map of the riser as the gas is migrating and give insight into gas expansion in low pressure.
4. Improvements to the riser simulation software created on LabVIEW, optimizing pumps and building feedback loops to compensate for the air entering the system.
5. Improvement to the support rack to allow for greater loads to compensate for anticipated switch from weighted mud instead of water as the flow medium. Possible rack modification to accommodate larger diameter pipe will provide a more accurate simulator.
6. Add hydraulics to riser support to allow heavier loads to be suspended when running tests at various inclinations.
7. Acquire additional high speed cameras to record Gas Migration and provide improved visual analysis of the bubble behavior.
8. Install multiphase meters at the discharge to the EC-Pump to log the amount of gas that is diverted and to obtain a gas fraction.

9. Replace the current 1 inch PVC pipe with a 2 inch diameter PVC pipe for simulation of top-fill.

10. Install additional VFD to control a third pump to provide higher flow rates for Top-Fill.

11. Rotate the discharge to the EC-Pump so that the elbow coming out of the riser is facing up, to eliminate the air trap at the discharge.

12. Purchase larger mud tanks and mixer, along with a viscometer, temperature transducer, and scale to prepare weighted mud.

13. Install improved Data Acquisition Board to log data from multiple sensors and transducers. The Data Acquisition Board should provide 4-8 Analog Output Signals to control the 3 Variable Frequency Drives and 4 Electronically Controlled Valves.

6. CONCLUSIONS

The purpose of this study was to design and install a Lab-Scale Marine Riser Simulator at Texas A&M University to study gas migration while drilling offshore wells using the EC-Drill™ Method. The main guidelines were provided by the EC-Drill™ Technology provider and additional literature was used to supplement the function and operations of this technology in mitigation of gas migration.

1. A lab-scale marine riser simulator was installed at the DGD Laboratory located at the University Services Building at Texas A&M University in College Station, TX.

2. The scaled riser simulator is a one-third (⅓) scaled model of an actual Marine Riser, the scaled model has a diameter of 6 in and a length of 27 ft.

3. The scaled riser simulator was constructed on a support rack, capable of tilting the scaled simulator from horizontal to vertical, allowing tests to be run at any desired inclination.

4. The scaled riser simulator contains two mud pumps rated for 105 GPM to provide the appropriate minimum annular flow velocity through the riser simulator which is equivalent that of the actual marine riser flowing at 1000 GPM.

5. The scaled riser simulator is currently set-up to operate in two modes:

- Full Circulation Mode: where the mud is fully circulated through a 2” Drill Pipe located in the center of the riser simulator,

- Annular Flow Mode: where mud is directly introduced into the system from the lower part of the annulus of the riser instead of full circulation.

6. The riser contains a discharge port at 8 ft. from the bottom to simulate the EC-Drill™ discharge pump. The exiting fluid is fed to the second pump and circulated back to the mud tank.

7. The riser contains a gas inlet port, located at the lower section of the pipe currently allowing compressed air to be injected into the system to simulate gas migration.

8. Two pressure transducers are installed on the riser, one located at the inlet for the annular flow mode, and a second transducer located on the riser at the level of the discharge to the EC-Pump.

9. Two video cameras record video footage of the migrating gas bubbles through the riser. The first camera is located at the discharge to the EC-Pump to monitor gas bubble behavior and direction, the second camera is located at 12.5 ft. to observe the gas bubble behavior and size.

10. A data logger is installed to log pressure and flow meter data and to control the pumps, allowing the operator to run the simulator at desired modes and flow rates.

11. From the results of initial experiments using water as drilling mud and air as gas, the flow rates at which the pumps operate are insufficient for comparison with field data.

12. Flow meter calibration was performed for low rates due to the inadequate testing capabilities for calibration. As a result, high flow rates contain large error.

13. Water contains low viscosity and gel strength, and this allows gas bubbles to migrate and form a single bubble making it more difficult to study migration and manipulate gas migration direction.

14. Additional pressure transducers would allow a better observation of the pressure profile throughout the riser.

15. The minimum flow requirement for the Coriolis meter on this simulator is 0.5 SCFM. This rate is too high to form a flow mixture of less than 0.1 gas fraction.

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APPENDIX A

OPERATING PROCEDURE OF LAB SETUP – FULL CIRCULATION MODE

1. Tighten ratchet straps to secure the Flow Loop onto the rack.
2. Turn on LabVIEW software to Primary EC-Drill™ Riser Simulator V.1.1.
3. Hit the "UP" button to activate the Winch and lift the Rack to the desired inclination. The Winch motor has a kill switch installed to prevent over pulling the rack. The kill switch kills the motor once 90 degree angle has been reached from the horizontal.
4. Connect Gas Line to the Flow Loop.
5. Open the Mud Tank Valve to prime The Mud Pump. **Fig. 56** displays the Mud Pump and the EC-Pump.

Fig. 56 – Mud Tank Valve

6. Close Drain Valve to prevent fluid from leaving the system. Drain Valve system is displayed in **Fig. 57**.

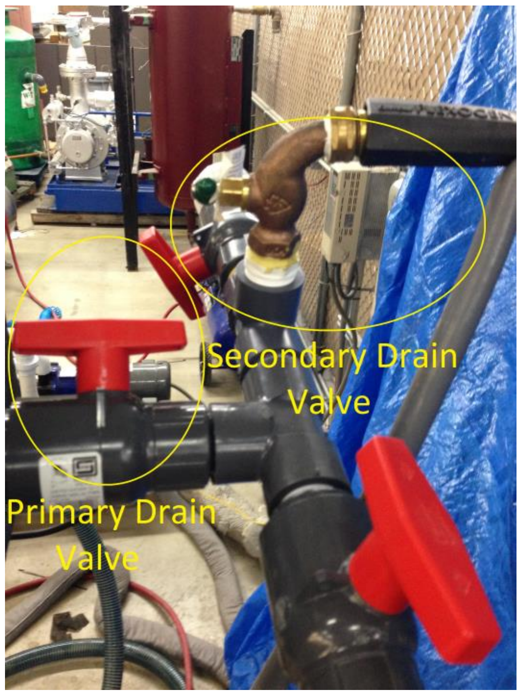

Fig. 57 – Drain Valves

7. Attach Line 1 (2" Hose) coming out of the mud pump and to the Full Circulation Line located at the lower part of the riser simulator. Close the Drain Line located at the bottom section of the Full Circulation Line.
8. Attach Line 2 (2" Hose entering the EC-Pump) on to the Discharge Line from the riser simulator. The Discharge Line is located on the clear tee.

9. Close the Secondary Inlet Line located at the front part of the riser. (SECONDARY INLET is used to simulate only annular return and not full circulation)
10. Open the all valves located on the manifold exiting the mud pump and the EC-Pump. The valve system is displayed in **Fig. 58**.

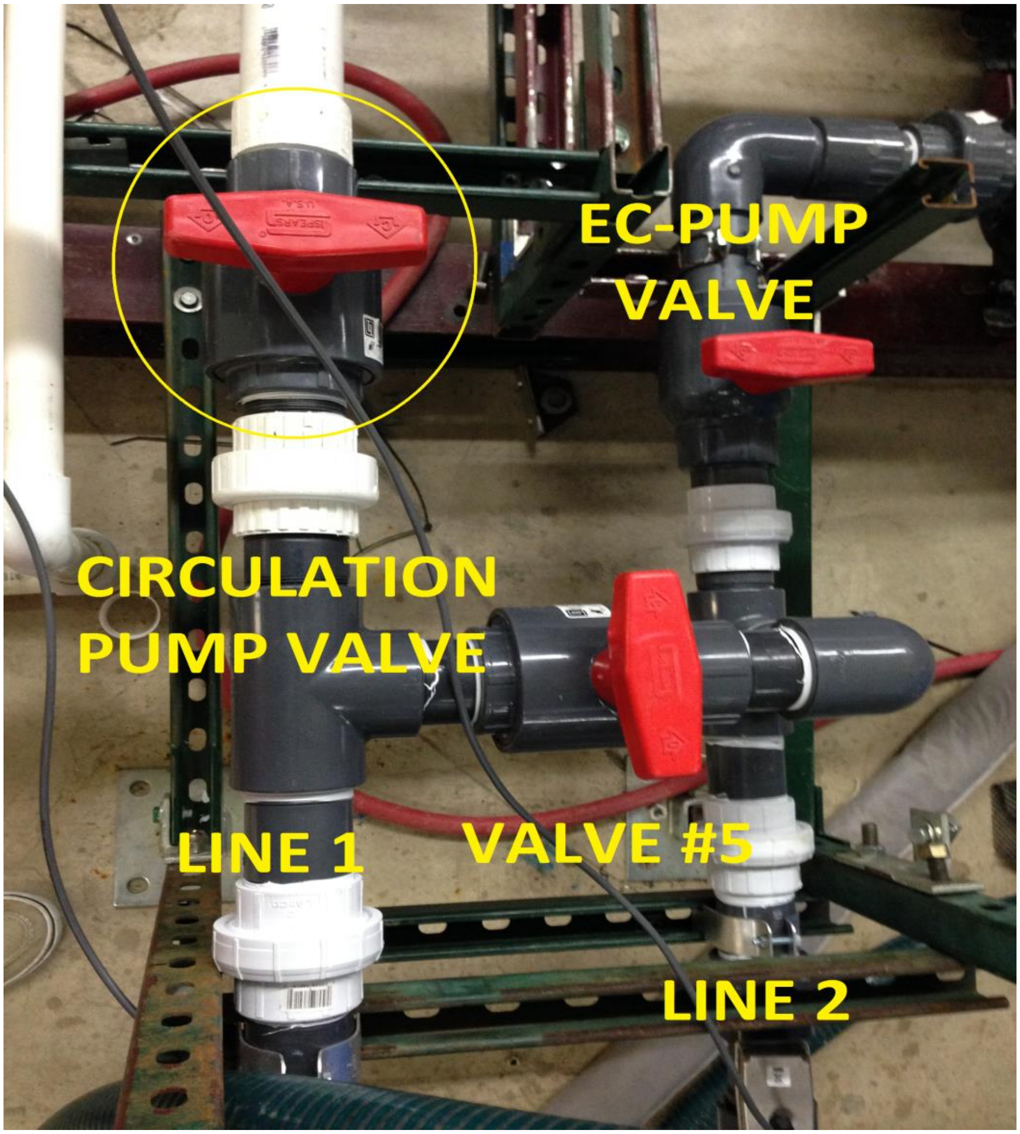

Fig. 58 – Valve and Line Arrangement for Circulation Lines

11. Run EC-Drill™ Riser Simulator v.1.1 and adjust Mud Pump Frequency to desired value and activate power switch. (Do not run pumps dry. Do not run Pump 2 until fluid level fills the entire discharge tee otherwise this will damage the pumps)
12. Allow system to fill main riser pipe annulus up to the EC-Drill™ discharge tee and once all air is removed from Line 2 activate EC-Pump to the desired discharge rate.
13. Monitor fluid level and do not overflow the riser simulator.
14. Once fluid level has reached desired level turn on gas line and begin allowing gas to enter the system. Adjust the screw valve to the desired gas flow rate and monitor bubble size.
15. Once system reaches a stable condition, open top fill valve displayed in **Fig. 59** and begin pumping water to the annulus of the riser simulator from the top of the system.

Fig. 59 – Top Fill Line Configuration

16. Perform tests and the data will be logged once the simulation has ended.
17. Adjust pump rates to the desired level and for best results start new simulation with every adjustment.
18. To end test, end simulation and kill the pump switches located on the data logger to switch to manual control on the VFD.
19. Turn off gas, close valve located on the gas line and detach gas line. Do not leave gas line attached in case there is a leak to prevent gas pressure build up in the PVC which could lead to dangerous results.
20. Close the top fill valve and open the tank valve to allow mud located on the top fill line to circulate in to the mud tank.
21. Allow the fluid in the riser simulator to be U-tubed back in to the tank, close the valve exiting the Mud Pump.
22. Open valve #5 to allow Line 1 to circulate into the Line 2 to empty the entire system and lower the fluid level to be able to detach the Hose.
23. Activate VFD #2 and let the EC-Pump empty the system and lower the fluid level in the hose.
24. Turn off VFD #2 once the fluid level is lowered and close the valves located on the manifold controlling the circulation.
25. Detach Line 1 and attach it to the secondary inlet located in the front of the riser simulator to empty the remaining 7 ft. water column.

26. Open Valve #5 and the valve located at the inlet of the EC-Pump and Run VFD 2 to empty the remaining fluid column.
27. Allow the fluid to be removed from the riser simulator and the line #1, kill the VFD #2 and close all valves on the pump manifold.
28. Open drain line to drain all remaining fluid in the system.
29. Detach top fill connection and empty the line.
30. Detach Line 1 and Line 2 Hose.
31. Hit the Down button on the Winch to lower the riser simulator.
32. Kill VFD switches and turn off Power Strip 2 to turn off the power supply to the data logger, sensors and meters.

APPENDIX B

OPERATING PROCEDURE OF LAB SETUP – ANNULAR FLOW MODE

1. Tighten Ratchet Straps to secure the Flow loop onto the rack.
2. Turn on LabVIEW Software to Primary EC-Drill™ Riser Simulator V.1.1.
3. Hit the “UP” button to activate the Winch and lift the rack to the desired inclination. The winch motor has a kill switch installed to prevent over pulling the rack. The kill switch kills the motor once 90 degree angle has been reached from the horizontal.
4. Connect gas line to the flow loop.
5. Open the Mud Tank Valve to prime the Mud Pump.
6. Close Drain Valve to prevent fluid from leaving the system.
7. Attach the Line 1 (2” Hose) coming out of the Mud Pump and attach to the Secondary Inlet Line displayed in **Fig. 60** located on the front of the Riser Simulator. Open the drain line located at the bottom section of the Full Circulation Line to prevent a pressure build up.

Fig. 60 – Secondary inlet for Annular Flow Mode

8. Attach the Line 2 (2” Hose entering the EC-Pump) on to the discharge line from the Riser Simulator. The Discharge Line is located on the Clear Tee.
9. Open Secondary Inlet Line Valve to allow annular flow mode.
10. Open the all valves located on the Manifold exiting the Mud Pump and the EC-Pump.
11. Run EC-Drill™ Riser Simulator V.1.1 and adjust Mud Pump Frequency to desired Value and activate Power Switch. (Do not run Pumps Dry. Do not run Pump 2 until Fluid level Fills the entire Discharge Tee otherwise this will damage the pumps)
12. Allow system to fill Main Riser Pipe Annulus up to the EC-Drill™ Discharge Tee and once all air is removed from Hose Line 2 activate EC-Pump to the desired discharge rate.
13. Monitor Fluid level and do not overflow the Riser Simulator.
14. Once Fluid level has reached desired level turn on gas line and begin allowing gas to enter the system. Adjust the Screw Valve to the desired gas flow rate and monitor bubble size.
15. Once system reaches a stable condition, open top fill valve and begin pumping water to the annulus of the riser simulator from the top of the system.
16. Perform tests and the data will be logged once the simulation has ended.
17. Adjust Pump rates to the desired level and for best results start new simulation with every adjustment.
18. To end test, end simulation and kill the pump switches located on the data logger to switch to manual control on the VFD.

19. Turn off gas, close Valve located on the gas line and detach gas line. Do not leave gas line attached in case there is a leak to prevent gas pressure build up in the PVC which could lead to dangerous results.
20. Close the Top Fill Valve and open the tank valve to allow Mud located on the top fill line to circulate in to the mud tank.
21. Allow the Fluid in the Riser Simulator to U-Tubed back in to the tank, close the Valve exiting the Mud Pump.
22. Open Valve #5 to allow Line 1 to circulate into the Line 2 to empty the entire system and lower the fluid level to be able to detach the Hose.
23. Activate VFD #2 and let the EC-Pump empty the system and lower the fluid level in the hose.
24. Turn off VFD #2 once the Fluid level is lowered and close the Valves located on the Manifold controlling the Circulation.
25. Open Drain line to drain all remaining fluid in the system.
26. Detach Top Fill hose and empty the line.
27. Detach Line 1 and Line 2 hose and zip tie to the Base of the support system
28. Hit the Down button on the Winch to lower the Riser Simulator.
29. Kill VFD switches and turn off Power Strip 2 to turn off the power supply to the data logger, sensors and meters.

APPENDIX C

LIST OF EQUIPMENT

1. Mud Pump – Iwaki Walchem Magnet Pump

   Model: MDH-425CV6-D

   Head (Ft): 106 @ 5 GPM – 82 @ 115 GPM

   5 HP, 60 Hz, 3440 RPM

2. EC-Pump – Iwaki Walchem Magnet Pump

   Model: MDH-425CV6-D

   Head (Ft): 106 @ 5 GPM – 82 @ 115 GPM

   5 HP, 60 Hz, 3440 RPM

3. Mud Tank: Chem – Tainer 100 Gallon Vertical Bulk Storage Tank

   Part Number: TC2364IA

   Rated Fluid: (1.9 S.G)

   Dimensions: 23” D X 64” H, 100 Gallons, 40 Lbs.

4. Liquid Flow Meter: GPI Water Meter

   Model: TM200-N-P- 2” Turbine Meter

   Fitting: NPT (Female)

   Flow Range: 20 – 200 GPM

   Accuracy: ± 3.0 % of reading

Pressure Rating: 225 PSIG @ 73°F

Material: PVC

Located on outlet of Mud Pump and inlet of EC-Pump

5. Liquid Flow Meter: GPI Water Meter

   Model: TM050-N ½" Turbine Meter

   Fitting: NPT (Female)

   Flow Range: 1 – 10 GPM

   Accuracy: ± 3.0 % of reading

   Pressure Rating: 225 PSIG @ 73°

   Material: PVC

   Located on Top Fill Line

6. Coriolis Meter: Micromotion

   Model: F025S319CQBAEZZZZ

   S/N 13280047

   Material: Stainless Steel

   For Gas:

   Accuracy: ±0.5% of Mass Flow Rate

   Flow Rates: 17 lb./min – 388 SCFM at 14.7 Pisa and 60°F

   For Liquids:

   Accuracy: ±0.20% of Mass Flow Rate & ±0.28% of Volume Flow Rate

Maximum Flow Rates: 100 lb./min – 12 gal/min

7. Pressure Transducer 1 & 2: Validyne

   Model: P55D-2-N-4-42-S-4-A

   Measurement: Differential

   Output Type: 4-20mA

   Pressure Connection: 1/8” Female NPT w/8-32 Bleed Port

   Pressure Range: 20 Psi

8. Pressure Transducer 3: Validyne

   Model: P55D-2-N-4-40-S-4-A

   Measurement Differential

   Output Type: 4-20mA

   Pressure Connections: 1/8” Female NPT w/8-32 Bleed Port

   Pressure Range: 12.5 Psi

APPENDIX D

CALIBRATION OF PRESSURE TRANSDUCERS

Pressure Transducer 1

Brand and Model: Validyne P55D-2-N-4-42-S-4-A

Rating: 0-20 Psi @ 0-160 F

The Pressure Transducers were calibrated using a dead weight machine, using weights 0 lbs (no load), 5 lbs. and 20 lbs.

The Calibration table is below:

Calibration Data:

Table 3—Calibration Data for Pressure Transducer 1

Calibration Data	
Pressure (psi)	Voltage (V)
0	1.133665
15	3.745006
20	4.69529

Table 3 shows the calibration data for the pressure transducer. The pressure in psi in Column 1 and the voltage drop in column 2. This data was used to plot the graph displayed in **Fig. 61**.

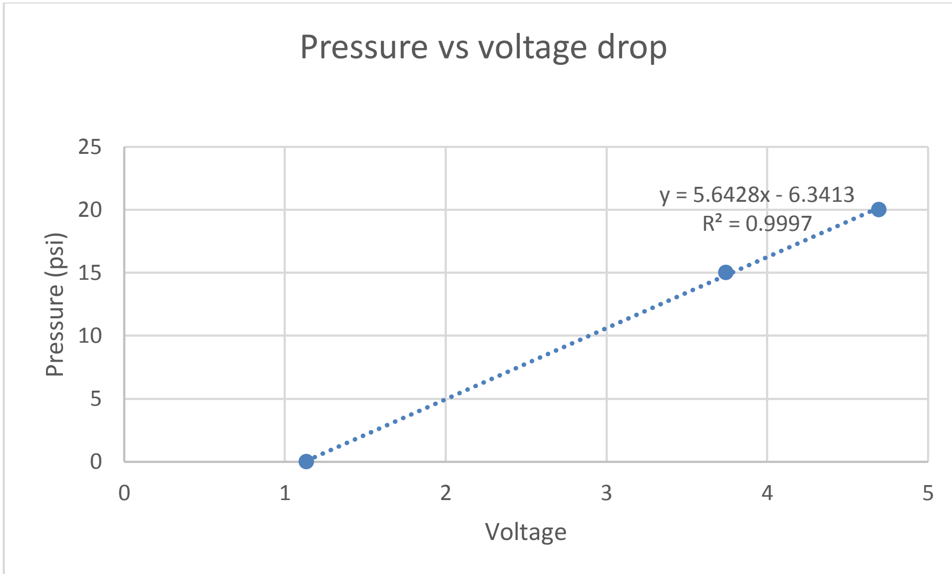

Fig. 61—Pressure Transducer 1 Calibration Graph

Fig. 61 was obtained by plotting the pressure and voltage drop from the calibration. The figure was fitted with a linear trend line and the equation below was obtained.

$$y = 5.6428x - 6.3413$$

This equation was entered in the LabVIEW Riser Simulation Software to convert, display and log the pressure data.

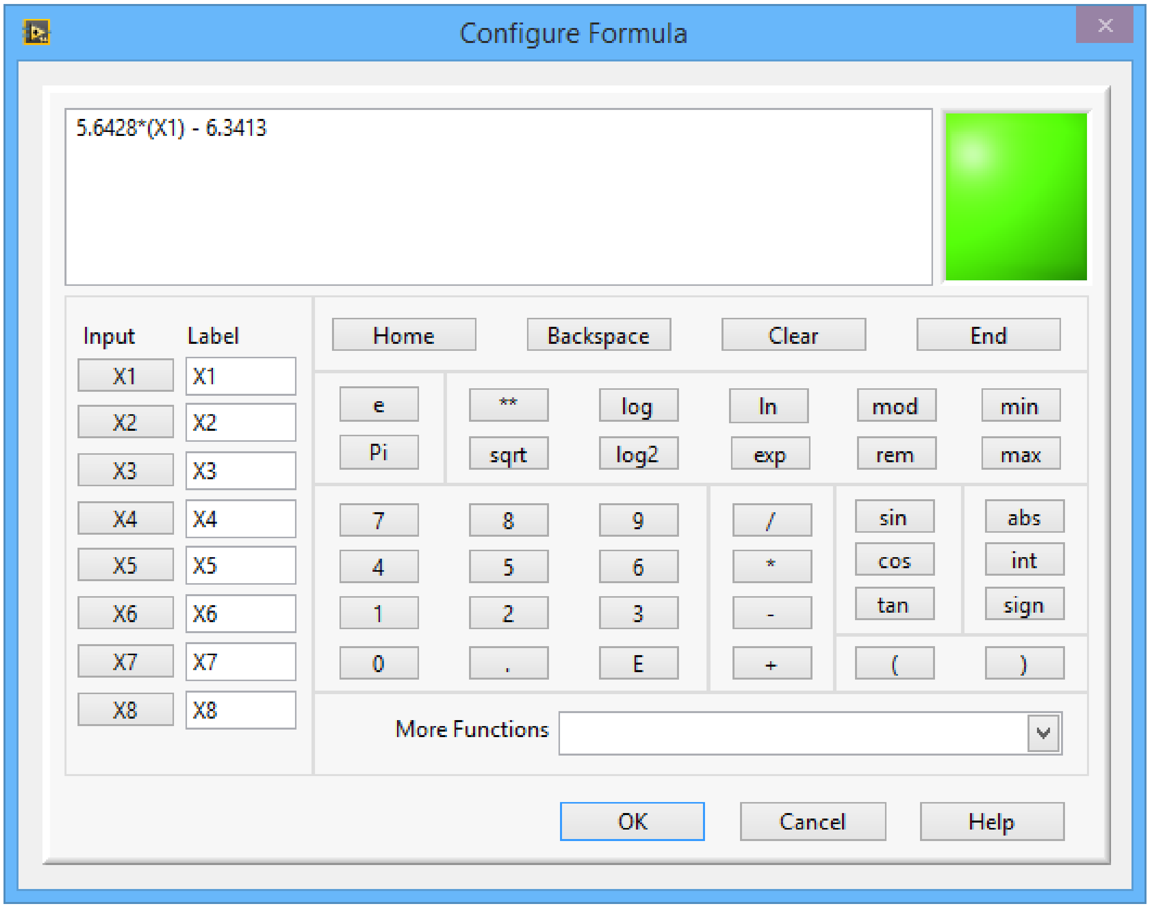

Fig. 62—LabVIEW Equation Window for Pressure Transducer 1

Fig. 62 shows the equation used in LabVIEW to convert the voltage drop data to pressure in units of psi for Pressure Transducer 1

Pressure Transducer 2

Brand Model: Validyne P55D-2-N-4-42-S-4-A

Rating: 0-20 Psi @ 0-160 F

Calibration Data:

Table 4—Calibration Data for Pressure Transducer 2

Calibration Data	
Pressure (psi)	Voltage (V)
0	0.943513272
15	3.772932814
20	4.742626496

Table 4 shows the calibration data for the pressure transducer 2. The pressure in psi in column 1 and the voltage drop in column 2. This data was used to plot the graph displayed in **Fig. 63**.

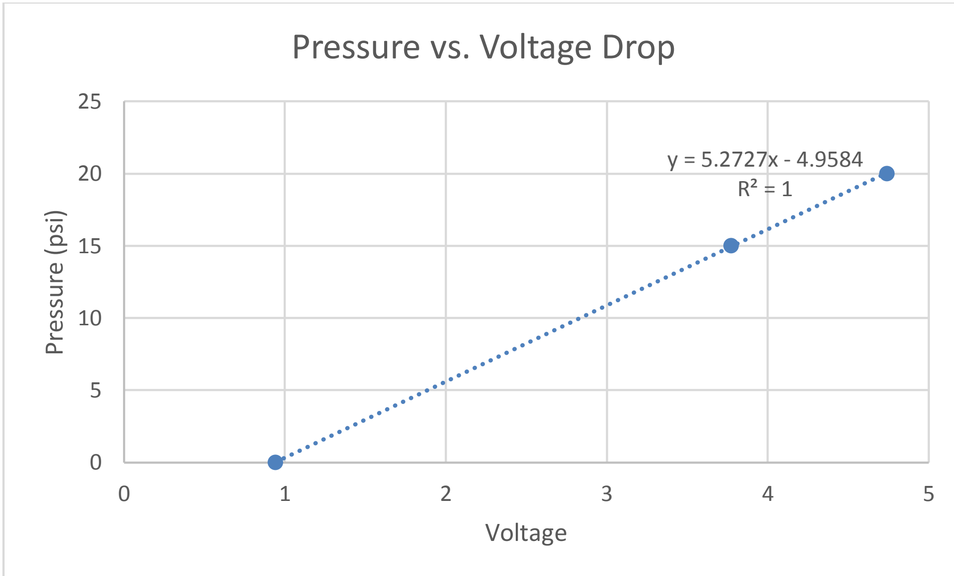

Fig. 63—Pressure Transducer 2 Calibration Graph

Fig. 63 was obtained by plotting the pressure and voltage drop from the calibration. The figure was fitted with a linear trend line and the equation below was obtained for pressure transducer 2.

$$y = 5.2727x - 4.9584$$

This equation was entered in the LabVIEW Riser Simulation Software to convert, display and log the pressure data.

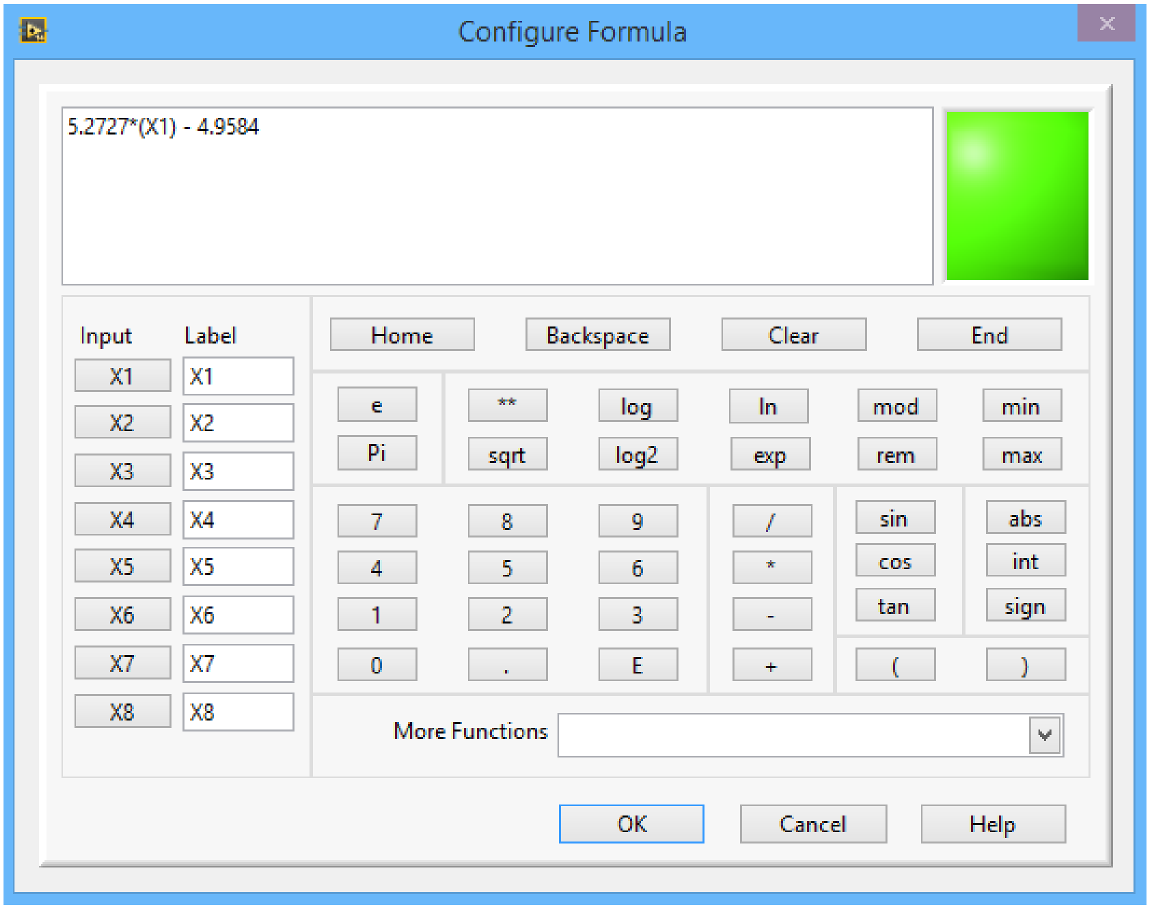

Fig. 64—LabVIEW Equation Window for Pressure Transducer 2

Fig. 64 shows the equation used in LabVIEW to convert the voltage drop data to pressure in units of psi for pressure transducer 2.

Pressure Transducer 3

Brand Model: Validyne P55D-2-N-4-40-S-4-A

Rating: 0-12.5 Psi @ 0-160 F

This Pressure Transducer was calibrated using the dead weight machine. Since this transducer is rated for lower pressure it was calibrated using weights 0 lbs., 5 lbs. and 10 lbs.

Calibration Data:

Table 5—Calibration Data for Pressure Transducer 3

Calibration Data	
Pressure (psi)	Voltage (V)
0	1.236167048
5	2.857694299
10	4.487034341

Table 5 shows the calibration data for the pressure transducer. The pressure in psi in column 1 and the voltage drop in column 2. This data was used to plot the graph displayed in **Fig. 65**.

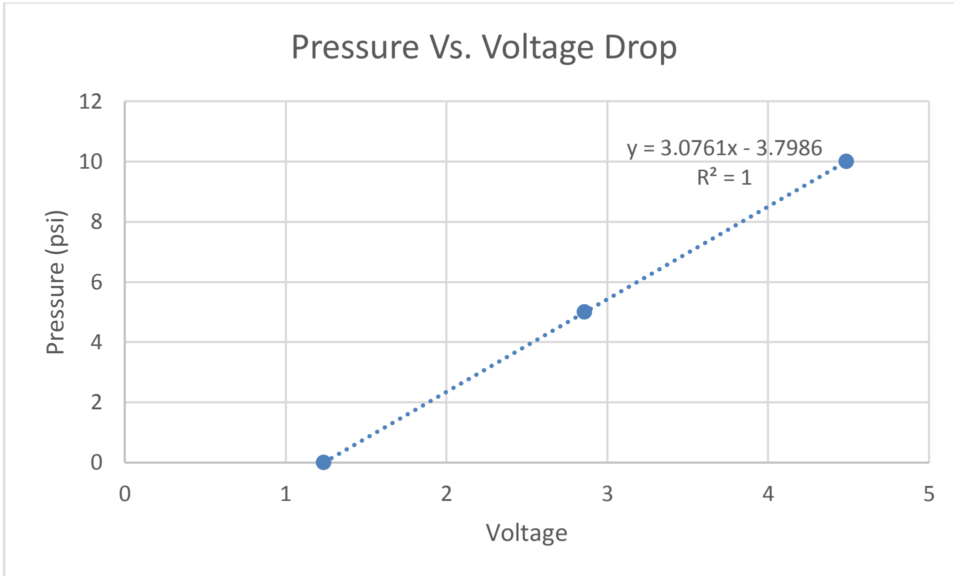

Fig. 65—Pressure Transducer 3 Calibration Graph

Fig. 65 was obtained by plotting the pressure and voltage drop from the calibration. The Fig. was fitted with a linear trend line and the equation below was obtained for Pressure Transducer #3.

$$y = 3.0761x - 3.7986$$

This equation was entered in the LabVIEW Riser Simulation Software to convert, display and log the pressure data.

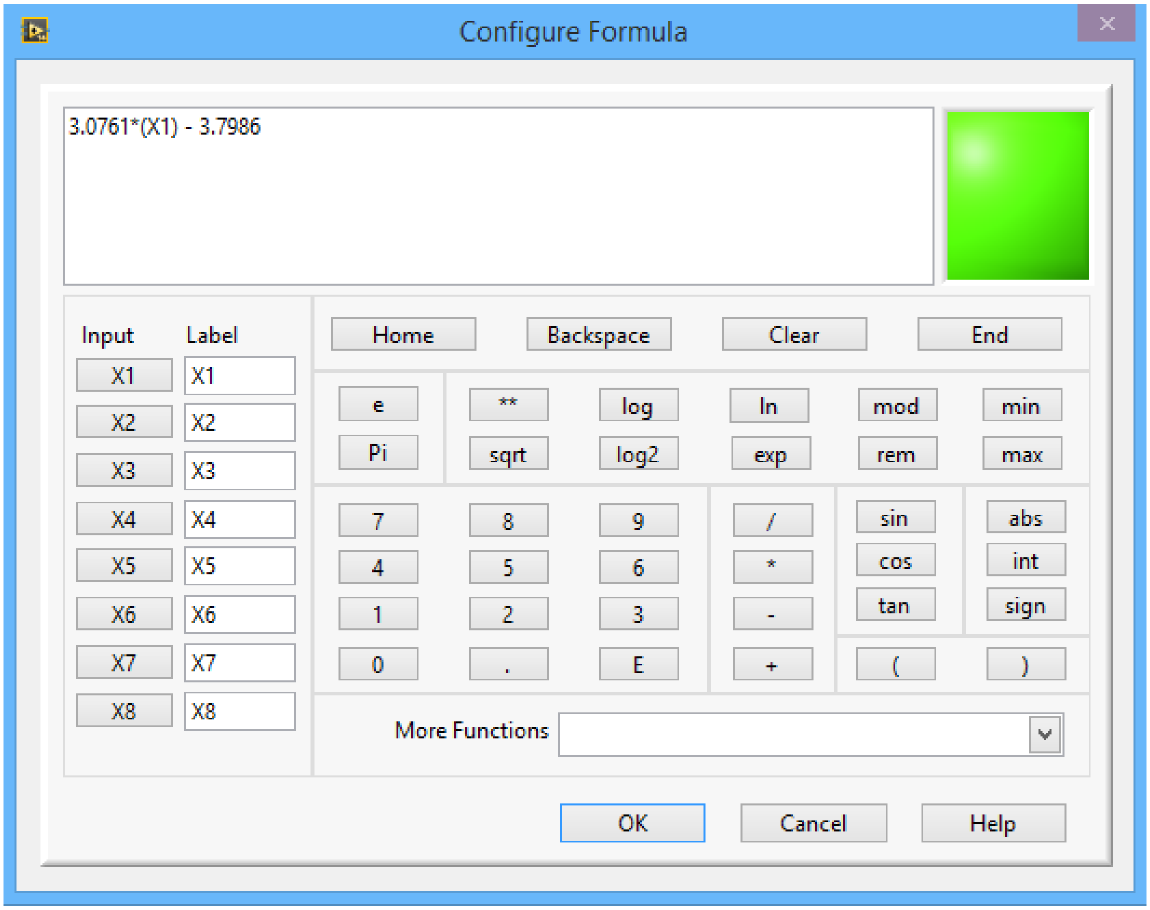

Fig. 66—LabVIEW Equation Window for Pressure Transducer 3

Fig. 66 shows the equation used in LabVIEW to convert the voltage drop data to pressure in units of psi for pressure transducer 3.

APPENDIX E

CALIBRATION OF FLOW METERS

The GPI TM200-N-P flow meters were calibrated using the bucket test method. The 40 Gal Tank below was used.

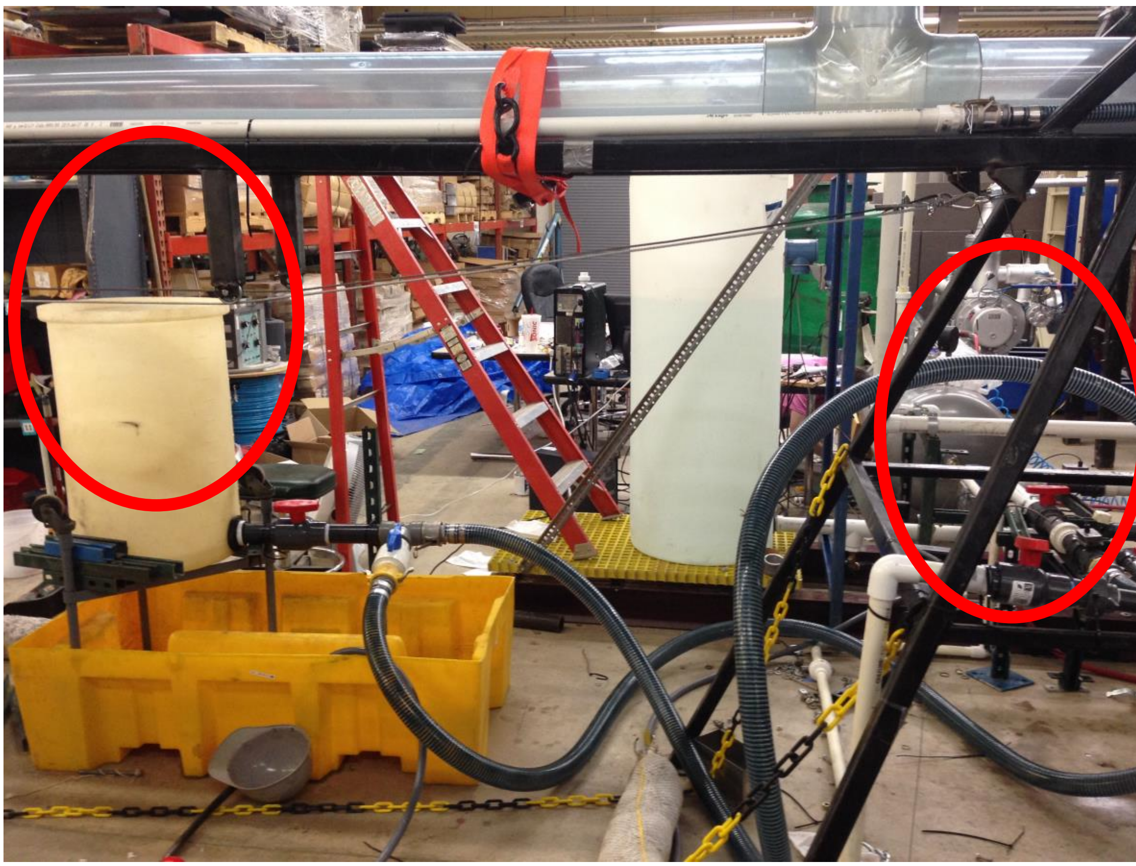

Fig. 67—Flow Meter Calibration Bucket Test

Fig. 67 shows the calibration bucket test setup. The pumps were connected to the tank on the left side of the image and meters are located on the left side of the image. The Pumps were activated at pre-selected frequencies and the output flow meter frequency was logged along with the time for each 2.5 gallon interval in the 40 Gal tank.

The pumps were ran at 15, 20, 25, 30, 35, 40 and 45 Hz frequencies and calibrated to the frequency of the output signal from the flow meters. This was then plotted against the time it took to fill each 2.5 gallon interval on the bucket test.

The calibration data tables for each VFD frequency are given below in **Tables 6 through 12**.

Table 6—Calibration of Mud Flow Meters at 15 Hz VFD Frequency

Data Point	1	VFD Frequency		15	Hz
	time (s)	Volume (gal)	Flow Meter 1 (hz)	Flow Meter 2 (hz)	
	3.21	2.5	69.78974266	69.5499926	
	3.75	2.5	68.08917794	68.10012505	
	3.79	2.5	67.05756396	66.80826385	
	3.61	2.5	65.71621599	65.72528956	
	3.93	2.5	65.0374725	64.53672471	
	4.06	2.5	63.83820101	63.40645122	
	3.91	2.5	62.83614887	62.26044369	
	4.21	2.5	61.5628978	61.15191201	GPM
Average	3.80875	2.5	65.49092759	65.19240034	39.383

Table 7—Calibration of Mud Flow Meters at 20 Hz VFD Frequency

Data Point	2	VFD Frequency		20	Hz
	time (s)	Volume (gal)	Flow Meter 1 (hz)	Flow Meter 2 (hz)	
	2.78	2.5	91.98222321	91.8418992	
	2.95	2.5	90.55478878	90.61332928	
	3.01	2.5	89.55034802	89.50568122	
	2.81	2.5	88.35678927	88.18454764	
	2.78	2.5	87.12953329	87.07838562	
	3.26	2.5	86.1838521	86.02703614	
	2.93	2.5	85.46765048	85.01110139	
	3.06	2.5	84.02391477	83.6644641	GPM
Average	2.9475	2.5	87.90613749	87.74080557	50.89059

Table 8—Calibration of Mud Flow Meters at 25 Hz VFD Frequency

Data Point	3	VFD Frequency		25	Hz
	time (s)	Volume (gal)	Flow Meter 1 (hz)	Flow Meter 2 (hz)	
	2.71	2.5	108.0363429	108.1710418	
	2.21	2.5	107.0048713	107.0070961	
	2.2	2.5	106.4481134	106.2012222	
	2.43	2.5	104.9834929	105.0792779	
	2.33	2.5	104.2045632	104.255932	
	2.53	2.5	103.48073	103.3403657	
	2.59	2.5	103.3958732	102.4114012	
	2.61	2.5	102.2805316	101.437953	GPM
Average	2.45125	2.5	104.9793148	104.7380362	61.19327

Table 9—Calibration of Mud Flow Meters at 30 Hz VFD Frequency

Data Point	4	VFD Frequency		30	Hz
	time (s)	Volume (gal)	Flow Meter 1 (hz)	Flow Meter 2 (hz)	
	1.74	2.5	127.5121578	127.5358004	
	2.49	2.5	126.5263282	126.5876869	
	1.91	2.5	126.276135	125.9431238	
	1.98	2.5	125.0368722	124.9824416	
	2.2	2.5	124.2595149	124.0180377	
	1.98	2.5	123.2507095	123.336049	
	2.13	2.5	122.1453242	121.9297138	
	2	2.5	121.6676317	121.3020094	GPM
Average	2.05375	2.5	124.5843342	124.4543578	73.03713

Table 10—Calibration of Mud Flow Meters at 35 Hz VFD Frequency

Data Point	5	VFD Frequency		35	Hz
	time (s)	Volume (gal)	Flow Meter 1 (hz)	Flow Meter 2 (hz)	
	1.81	2.5	155.0778976	153.8806588	
	1.73	2.5	154.4857956	153.0116712	
	1.6	2.5	154.1253522	152.7393352	
	1.68	2.5	153.3940428	152.2579294	
	1.91	2.5	152.2373886	150.9261077	
	1.76	2.5	151.3591489	150.0900859	
	1.63	2.5	151.0819916	149.5186266	
	1.65	2.5	149.6711739	148.7002156	GPM
Average	1.72125	2.5	152.6790989	151.3905788	87.14597

Table 11—Calibration of Mud Flow Meters at 40 Hz VFD Frequency

Data Point	6	VFD Frequency		40	Hz
	time (s)	Volume (gal)	Flow Meter 1 (hz)	Flow Meter 2 (hz)	
	1.49	2.5	182.1105286	182.0916156	
	1.38	2.5	180.9456475	181.2985651	
	1.56	2.5	180.4077916	180.7555598	
	1.68	2.5	179.7444169	180.1030013	
	1.38	2.5	178.9166706	179.1005507	
	1.41	2.5	178.8642027	178.5654021	
	1.48	2.5	178.0010571	177.9803308	
	1.49	2.5	177.9321857	177.7963411	GPM
Average	1.48375	2.5	179.6153126	179.7114208	101.0952

Table 12—Calibration of Mud Flow Meters at 45 Hz VFD Frequency

Data Point	7	VFD Frequency		45	Hz
	time (s)	Volume (gal)	Flow Meter 1 (hz)	Flow Meter 2 (hz)	
	1	2.5	209.9183472	207.8809342	
	1.23	2.5	209.0260624	207.1932652	
	1.23	2.5	208.6208165	206.4844978	
	1.3	2.5	207.3709409	206.0492719	
	0.98	2.5	206.7854054	204.8611473	
	1.18	2.5	206.5797597	204.7117478	
	1.35	2.5	205.9304099	203.7849658	
	1.23	2.5	204.8196421	203.084197	GPM
Average	1.1875	2.5	207.381423	205.5062534	126.3158

As seen in the Tables 6-12, the flowmeter frequency data is logged for each 2.5 gal interval and timed. The average Flow Meter Frequency was then used along with the average volume in gallon per time (min) was plotted to obtain a calibration equation.

Table 13—Summary of Flow Meter Calibration Data

Flow Meter Calibration			
VFD Frequency (Hz)	Average Flow Meter 1 Frequency (Hz)	Average Flow Meter 2 Frequency (Hz)	Average Flow Rate (GPM)
20	65.49092759	65.19240034	39.38299967
15	87.90613749	87.74080557	50.89058524
25	104.9793148	104.7380362	61.19326874
30	124.5843342	124.4543578	73.03712721
35	152.6790989	151.3905788	87.1459695
40	179.6153126	179.7114208	101.095198
45	207.381423	205.5062534	126.3157895

Table 13 summarizes all of the average flow meter frequency data and the average flow rate data for each VFD Frequency. This table is then used to create the calibration figure below.

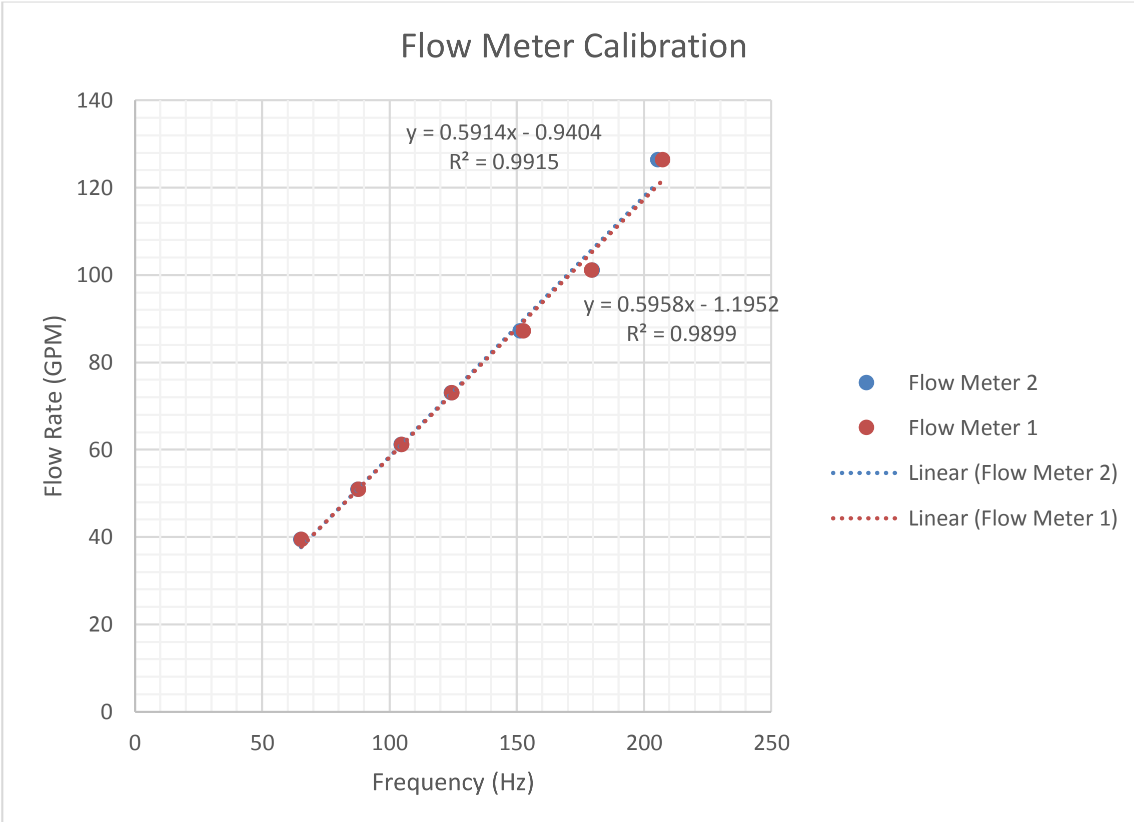

Fig. 68—Flow Meter Calibration Chart

Fig. 68 contains the data from the summary table. The two linear trend lines are used to produce the calibration equations for the flow meters.

The Flow Meter #1 Calibration equation:

$$Y = 0.5914 * X - 0.9404$$

The Flow Meter #2 Calibration equation:

$$Y = 0.5958 * X - 1.1952$$