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Abstract

This Master Thesis is dedicated to investigation of air bubbles behavior rising in counter current liquid flow as a part of research on Managed Pressure Drilling techniques. Implementing of MPD provides better pressure control by possibility to regulate well back pressure with choke and pump system. However, even with such a high level of pressure control kick situations could not be avoided. One of the possible scenarios for dealing with the kick is forcing the influx back to the formation by means of bull heading.

For experimental purposes, a 5 m experimental rig facility will be modified in order to create circulation system. Experiments will be conducted on 5 different fluids: water and PAC mixture with polymer concentration of 4g/l, 3 g/l, 2 g/l and 1 g/l. Density, viscosity and surface tension measurements are planned for all PAC mixtures. High FPS camera will be used to make a video of bubble behavior. Pressure readings will be conducted. A Ventury insert is planned to be installed in order to create pressure drop.

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1. Managed pressure drilling

1.1. General

The International Association of Drilling Contractors (IADC) defines MPD as:

''An adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the down hole-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.'' [1]

MPD has a several distinctive differences from conventional drilling, both from equipment and technological point of view. However, the main feature of MPD is the ability to control the annular pressure in the way that the well is constantly kept in balanced mode. Annular friction pressure is a complex parameter which represent the function of Hole geometry, Flow velocity, Fluid and cutting properties, Surface roughness. [2]

The ability to control back-pressure defines the working window in which MPD operations can be performed (Figure 1).

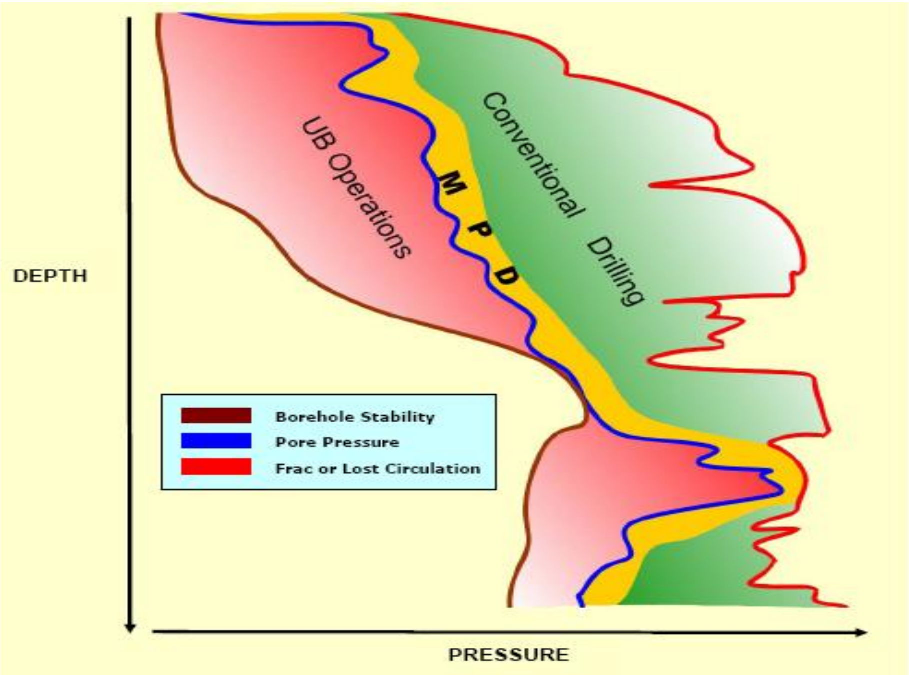

Figure 1. Working window for MPD and UBD operations.

Using of MPD techniques have several advantages compared to conventional such as, but not limited to are smaller size of the kick together with better kick control, possibility to drill wells, which were considered as undrillable, reduced risk and increased safety.

Another significant benefit of MPD is higher level of well control comparing to conventional drilling due to ability of immediately increasing of hydrostatic pressure once it is need, without spending time on increasing mud weight and circulation. The real time flow measurement provides immediate awareness and reaction on any losses or gains of fluid during drilling, preventing well control situations and undesirable events, such as gas in riser scenario. [3]

Also MPD is better than conventional in terms of increased quality of cementing job, because of precise control on pressure fluctuations while cementing and thereby avoiding or at least decreasing the possibility of cement losses to the formations and increase the accuracy of cement placement. [4]

However, while implementing MPD, some new safety, design, operational and maintenance issues need to be considered in order to eliminate or decrease drilling associated risks. [3]

Any MPD operation is implemented using either Reactive or Proactive approach. Reactive MPD aimed to mitigate any drilling issues as they arise, while Proactive MPD involves planning in advance to eliminate most of the possible drilling problems that might occur. [2] Obviously, Proactive MPD have higher level of complicity related to more detailed well engineering, different level of competency of rig crew, rig integration, logistics and equipment issues. [5]

However, with current trend to drill more and more complex wells (depth, pressure, temperature, depleted formations), Proactive MPD approach seems to be more suitable to future challenges. [2]

1.2. MPD system overview

During MPD operations the wellbore pressure is controlled by means of closed loop system. To prevent reservoir fluids from continuous flow to surface, amounts of surface backpressure may be applied as needed. A typical MPD system arrangement is shown at Figure 2. [2]

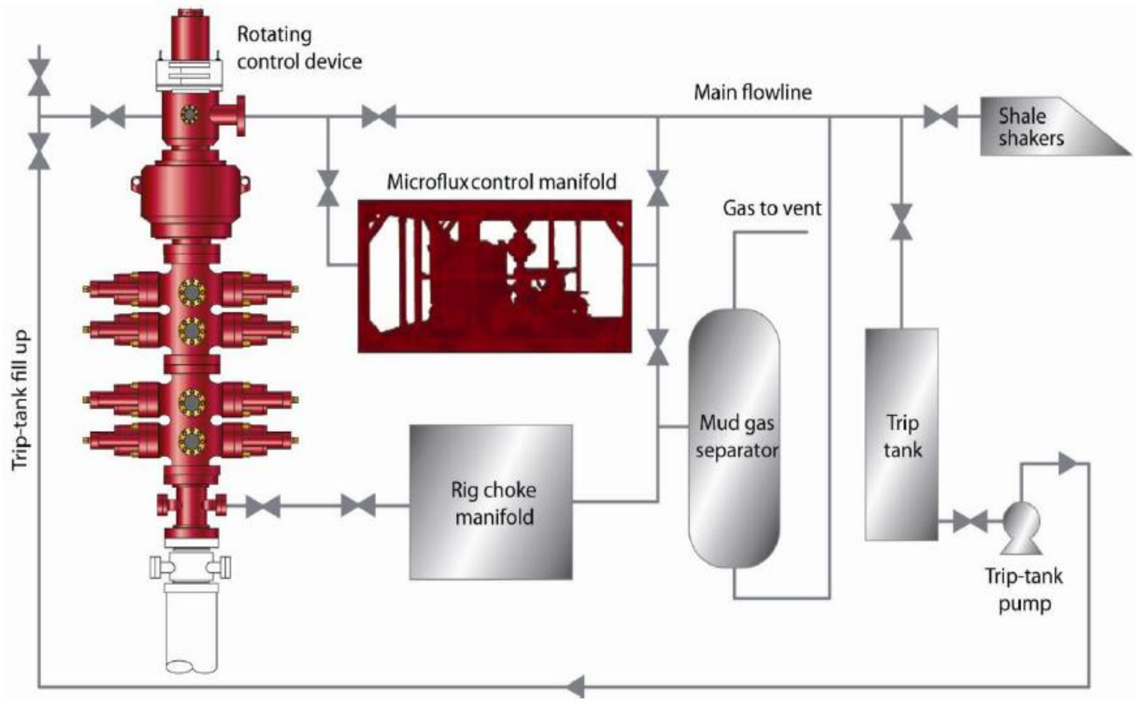

Figure 2. A typical MPD system arrangements [2]

MPD control systems include flow control unit and fluid diverter, choke panel and backpressure control. Fluid level in the annulus, fluid rheology, fluid density, hole geometry and circulating friction should also be controlled during MPD operations. [6]

Every MPD system should comprise at least five following elements:

- Rotating Control Devices (RCD)
- Choke
- Coriolis mass flow meter
- Non Return Valve (NRV)

Rotating control device (RCD) is the main pressure control element in any MPD system, most important and most common element. To keep annulus packed off during tripping, connection and drilling, RCD should provide such functions as flow diversion through choke to separation facilities, drill pipe rotation while the other functions are performed, annular pressure barrier maintenance. [2]

There are two main types of RCD: passive rotating control device and active rotating annular preventer.

Passive systems

This system is a rotating packer with undersized annular seals element. The using of this stripper rubber seals the pipe in normal pressure. Later the additional sealing is provided by annular back pressure. The seal element is sealed and locked in drilling assembly, that is lubricated and cooled by means of circulating hydraulic oil system.

Need for lubrication and cooling caused by the fact that the rubber rotates together with the pipe. As far as sealing element responds to annular back pressure, there is no need for personnel to regulate it during stripping and drilling operations. Some vendors nowadays use double sealing in RCD in order to provide additional safety. It should be noticed, that Passive systems are more common than Active.

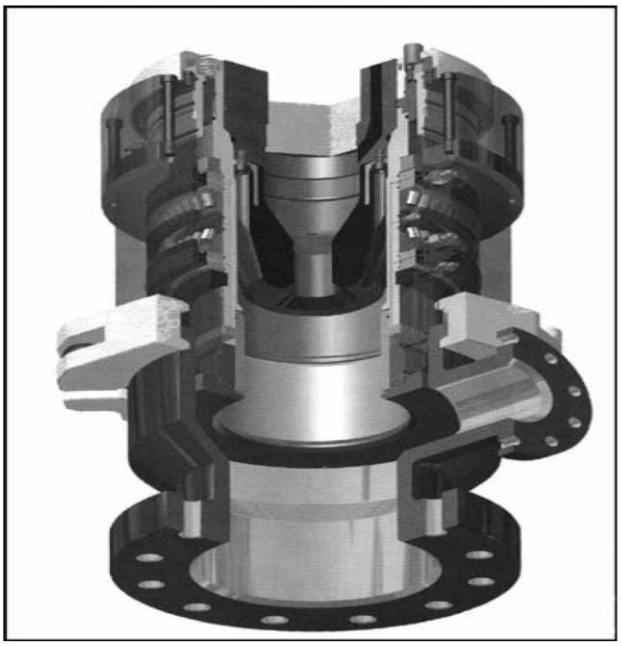

Figure 3. Example of Passive RCD System. [7]

Active systems.

The system is represented by annular packer, that is actuated hydraulically. It important to emphasize here, that it is not accepted as annular BOP. There are two hydraulic systems in the packer: one to open/close the preventer, another for lubricating and cooling the bearing assembly.

Packer pressure can be controlled either automatically or manually, open/close mode is conducted by personnel. Hydraulic system operates by electricity. Active system is newer and more complex idea comparing to Passive, due to higher amount of equipment. [7]

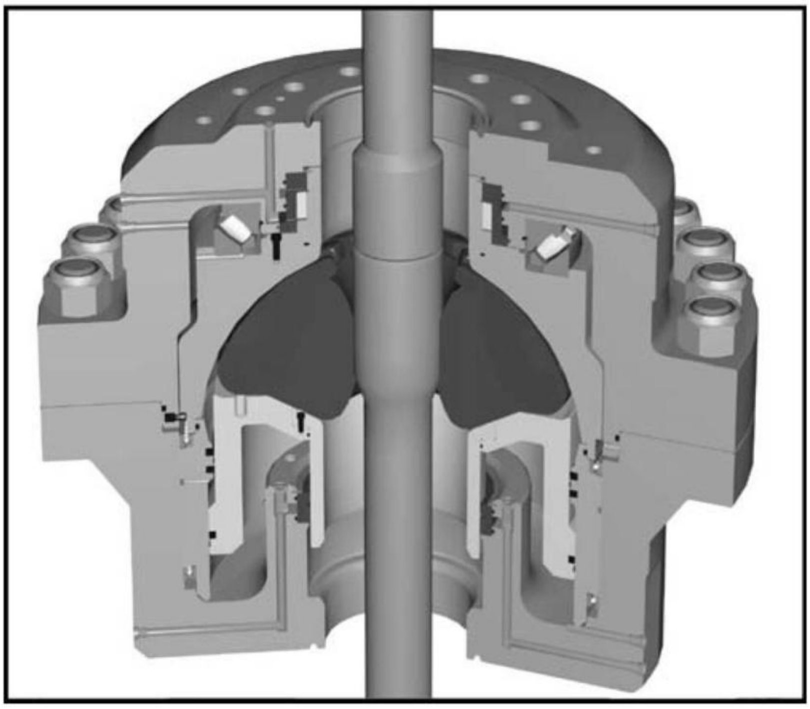

Figure 4. Example of Active RCD System. [7]

Wearing of RCD elements cannot be avoided. However, the installation of upper riser sealing equipment below the RCD will give the possibility for safety replacement of this elements. [3]

It should be noticed, that both system (as far as all BOP) have some snubbing force, because packer stripper hold up some of the pipe weight. That is lead to error in string weight and hence the WOB reading, which can become a problem in case when milling weights or light bit are necessary. [7]

MPD choke manifold have the main purpose to apply a back pressure prior to control the well by precisely controlling the flow. Chokes can be operated manually, semi-automatic and automatic. It is important to point out, that MPD chokes cannot be considered as a part of well control system, as far as a secondary well control equipment. [2]

Choke system is essential part of MPD equipment in terms of flow and pressure control. Chokes are always in use, so that is crucial for any MPD operation to have a separate choke system for well control and for MPD by itself. [7]

Coriolis mass flow meter

CMF is very sophisticated facility, which have several considerations to be used properly. First thing to be aware of, is that flow meter have a pressure drop, so it can be used only in closed pipe systems. Another issue is that accuracy of measurements decreases with decreasing of flow rate, so it shall works within higher limit, and this is especially challenging regarding to difference of designed flow rates for kick circulation and actual flow rates during drilling. So the balance should be found between capacity and accuracy during CMF selection. Moreover, CMF is very sensitive to gas presence. This is extremely important, because gas in flow meter will lead to wrong flow rate readings. [8]

Non Return Valves (NRV)

The valve that allows flow only in one direction, preventing the backward flow and make it possible to apply annulus back-pressure. In other words, the main purpose of NRV is to control U tube effects. [2]

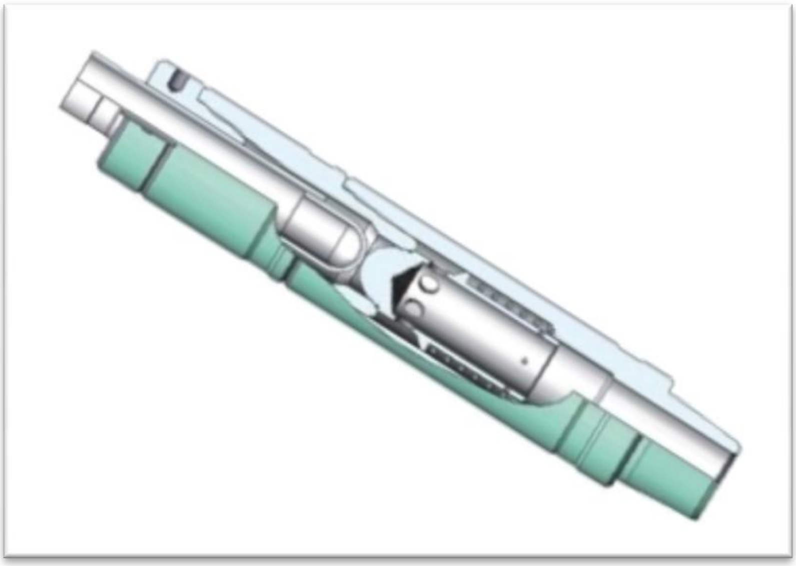

Figure 5. Non-Return Valve.

1.3 Variation of MPD techniques

MPD techniques are constantly evolving and at the moment can be categorized in a following groups: [2]

1. Subsea mud return (MPD)
2. Mud Cap Drilling (MCD)
3. Riserless mud return system (MPD)
4. Low riser mud return system (MPD)
5. Constant Bottom Hole Pressure (CBHP)

In this thesis, only few of them will be investigated in details prior to provide a basis for planned experiments.

Mud Cap drilling

Usually, MCD is used in such circumstances, when lost returns zones or/and hazardous gases such as H_2S is anticipated, and there is no way to eliminate this problems by using of conventional drilling methods. So MCD techniques allow to drill wells, that were considered as undrillable in such circumstances. However, there are some limitations for applying MCD, one should be aware of. For example, the formation drilled should have zones that can receive cuttings for anticipated period of time, also good trained personnel, complex equipment, large amounts of sacrificial and Mud Cap fluids should be avaible. [9]

During any type of MCD performed, if gas enters to the annulus the well control achieved by means of bull heading. Moreover, bull heading is an inherence part of any MCD operation, as far as fluids are pumped to the annulus (either constantly or periodically) in order to push any influxes back to the reservoir. Also any anticipated shale formations should be cased off in order to prevent swelling when contact the water, that is used as sacrificial fluid in MCD. [11]

In order to provide sufficient hole cleaning, torque and drag values are constantly controlled during drilling. Also, it is common practice to pump high viscous pill trough drill string just before a new pipe connection is going to be made. [12]

Mud Cap drilling can be classify into three main sub categories – floating, dynamic and pressurized MCD.

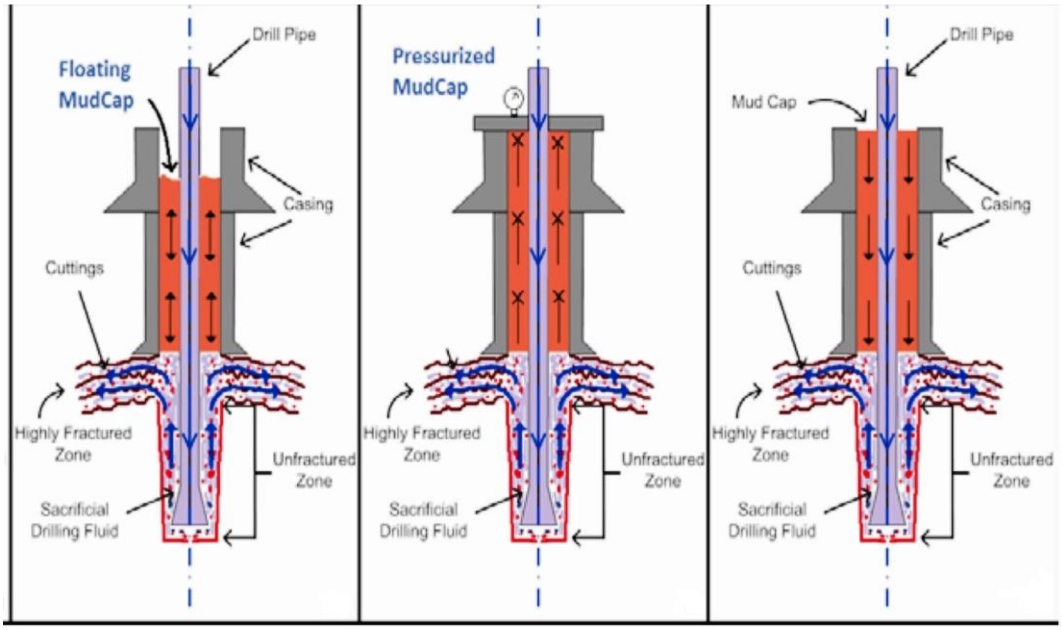

Figure 6.Variations of Mud Cap Drilling technology. [9]

FMCD

Can be considered as an option only when freshwater gradient is higher than formation pressure, e.g in underpressurized formations.

In this type of MCD the annulus surface is open to atmosphere, so the mud cap part of the column can move. The length of this column is designed in a way that the weight of this fluid provide sufficient hydrostatic head to equilibrate the formation pressure.

FMCD is the simplest sub category of MCD as far as it not requires any specific equipment like chokes or RCD, but on the other hand, it also one of the most challenging type, because the active determination of the level of Mud Cap at every point of time is quite hard task related to the high risks.

DMCD

In order to eliminate any single possibility of entering formation fluid into surface, a constant injection of MudCap fluid in annulus is performed. This variation of MCD is usually used when neither PMCD, nor FMCD can be performed. The logistics is more complicated and the price is the highest among all variations of MCD. On the other hand DMCD can be conducted in a most cases. [9]

PMCD

IADC definition of PMCD variation of MPD that involves “drilling with no return to surface, where an annulus fluid column, assisted by surface pressure, maintained above the formation that is capable of accepting fluid and cuttings” [1]

The pressurized mud cap drilling technique (PMCD) is used when a severe loss of circulation is anticipated, such as, but not limited to depleted formations or widely fractured carbonate formations. [2] It also should be noticed, that PMCD can be considered as an option only when freshwater gradient is lower, than formation pressure, e.g in overpressurized formations. [9]

To keep fluids from escaping, a heavy and viscous mud is pumped down the annulus, and then drilling operations is performed with light “sacrificial” fluid, which allows to improve drilling efficiency by increasing ROP. The main purpose of heavy fluid is perform as a mud cup, and thereby provide a well barrier and force any influx back to the depleted zone. Drilling cuttings also may be forced to depleted zone above.

Also, in order to maintain annular pressure, optional back-pressure can be applied. Obviously, the main advantage of using PMCD technique is the ability to control the well while experiencing severe fluid losses. [2]

In order to achieve a better pressure control, the Mud Cup is kept closed and pressurized at the surface. The pressure in the surface, usually called backpressure or choke pressure, is constantly monitored prior to control equilibrium state and well dynamic. The density of Mud Cap is very carefully designed in order to achieve the underbalance just above the fractured formation.

Despite of the presence of extra pressure at surface, PMCD in general related with lower risks, than FMCD, because the annulus pressure can be constantly controlled by means of backpressure. [9]

In order to perform PMCD operation, the rig must be equipped with RCD and high pressure circulating system, large amounts of sacrificial fluid (e.g. seawater) should be avaible. [2]

It is very important to emphasis, that before implementing PMCD, an injection test should be conducted on annulus and drill string in order to check the ability of loss zone to receive desired amounts of sacrificial fluid and drilling cuttings within desired flow rates without exceeding designed pressure for drill string, annulus and RCD. [12]

Challenges in implementing PMCD

PMCD implementation can face a lot of challenges, however, with proper planning they can be mitigated. [10]

Geology and geophysics.

As far as PMCD is usually implemented in carbonate reservoirs, where huge loses is anticipated due to carst persistence, the main challenge from GG point of view will be determination of the top of carbonate formation. This problem can be solved by installation of gamma ray in BHA and reduction of ROP above anticipated carbonate formation. Also the formation pressure estimation can be very difficult due to large uncertainty of fractures in carbonates. This pressure uncertainty can be reduced by careful research on near wells data (if available).

Well design and engineering

Main challenges here are production casing setting, BHA performance and LAM management. In order to provide sufficient annular capacity and guarantee fully isolation from formations above, the good practice can be to install production casing in main carbonate body.

Vibrations are one of the main concerns while drilling carbonates. A common practice to eliminate vibrations is incorporating BHA with centralizers together with motor. Another significant benefit from using motor is increasing the RCD sealing elements lifetime.

Bit selection is extremely important during PMCD implementation. As far as tripping while PMCD is unwanted event, the bit should to be chosen to be durable enough to drill carbonate section in one run. However, drilling with high rates should be avoided, ROP together with drill bit should be chosen with intention to create small particles, which will properly fill formation fractures, reducing the possibility of stuck pipe.

Personnel

It is impossible to underestimate the human factor in drilling, especially during any kind of MPD, where are no commonly recognized standards establish and procedures vary in every company. That is why the level of competency of rig crew should be very high. Only experienced specialists should be allowed to perform PMCD operations. Also, specific trainings should be conducted.

Logistics.

The amounts of different fluids (e.g. MudCap fluid, LAM, chemicals) should be pre-calculated and available, as far as storage capacities for them. [10]

1.4 Well control considerations

MPD brings higher level of well control comparing to conventional drilling. [4] However, determination of the point where influx management ends and well control begins is one of the important parts of MPD operations. Typical approach here is to create MPD Operation Matrix, which clearly outlines all parameters to be controlled and procedures to be made. [13]

Primary well barrier in MPD represented by the hydrostatic column of fluid [13] and, as far as MPD equipment is the part of flow path, chokes and RCD can be categorized as part of primary barrier. The fluid column is the most crucial part of well barrier system, so it is should be constantly monitored to provide it's barrier functions. The Secondary barrier system for MPD is absolutely the same as conventional drilling and can be used for well control.

To protect the MPD system from overpressure in general and drilling riser in particular in case of applying too high backpressure, relies valves in buffer manifold can be used. [4]

During some kinds of MPD operations the wellbore is closed, so standard flow check procedure becomes impossible and that is leads to issues related to kick detection and well control. [8] However, the level of operations safety is higher when RCD is used [14]

Typically, the RCD outlet is divided between MPD choke manifold and main return flow line which installed in parallel.

There are four main reasons for losing primary well control during MPD implementation: lost circulation, swabbing, insufficient BHP caused by insufficient fluid density, failure in keeping well fully filed with mud during tripping.

Losses

Can be caused both by natural issues, such as depleted or highly fractured formations, and by personnel mistakes that lead to mechanical fracturing. If loss is occur, the back pressure should be decreased and well should be treated with increased attention.

Swabbing

It is more difficult to recognize swab in closed wellbore, especially when drilling with OBM.

Pressure

Despite of the fact that hole pressure can be controlled, the BHP still may be insufficient due to uncertainty in pore and formation pressures.

Kick circulation with MPD equipment

Typical sequence of actions here will be to continue a circulation increasing back pressure until the balance state will be achieved between flow in and flow out, and then use drillers method to circulate the kick out.

There are some pros of using MPD choke manifold in order to circulate the kick:

- avoidance of stuck pipe possibility, because pipe can be rotated during circulation.
- reducing the circulation time, because there is a possibility to have higher flow rates.[8]

1.5. Underbalanced Drilling (UBD)

Underbalanced drilling refers to any drilling operation that performed with designed BHP being lower than formation pressure. The underbalanced state can be natural or be achieved by adding the gas (e.g. nitrogen, natural gas, air) in the mud, resulting in decreasing hydrostatic weight of fluid column. The gas can be injected either through a standpipe or through Parasitic String.

The main purpose of that technique is to improve formation productivity by avoiding invasion of mud and drilling particles into formation as well as filter cake build up. Its important to notice, that underbalanced state can lead to influx of formation fluids into the well, thereby facilities and equipment for safety kick circulation must be presented. UBD uses closed circulation system for well control. Figure 5 shows the UBD system.

To perform UBD operation the following criteria must be satisfied:

P reservoir > P bottom hole > P well collapse

P bottom hole = P hydrostatic +P friction +P choke

The effective downhole circulating pressure of the drilling fluid (P bottom hole) is equal to the hydrostatic pressure of the fluid column, plus associated friction pressures, plus any pressure applied on surface (P choke). [2]

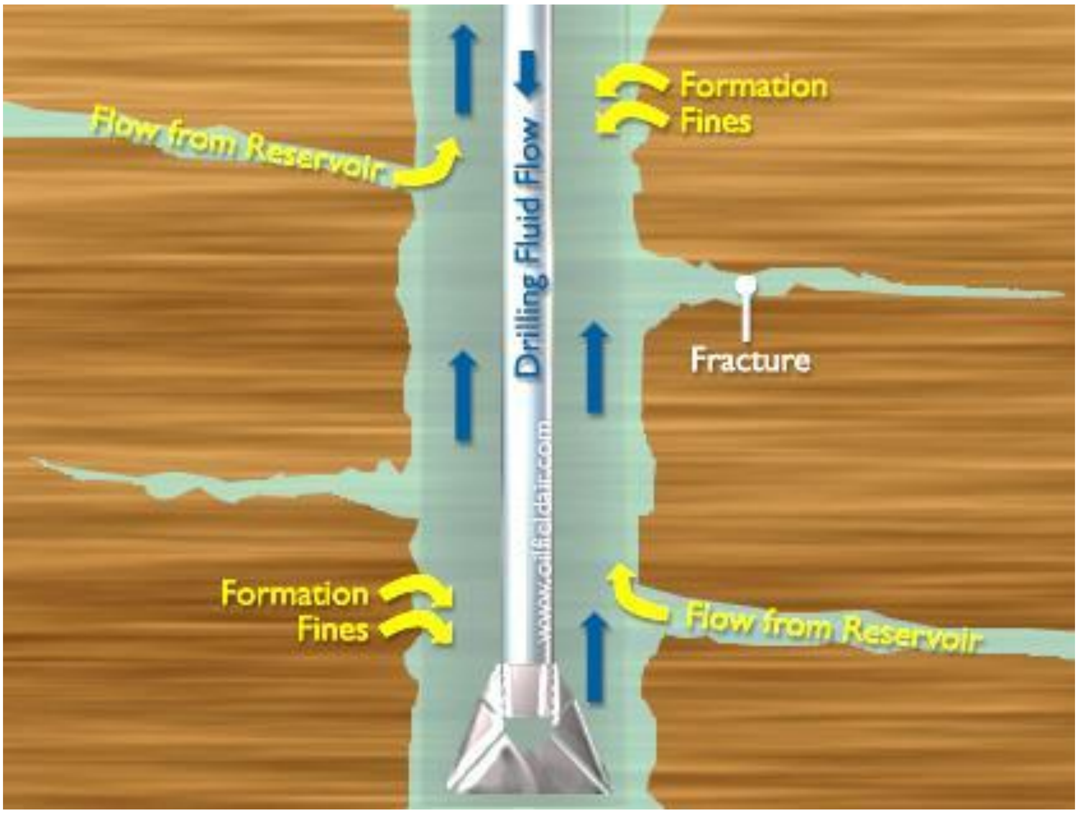

Figure 7. Underbalanced Drilling systems

The equipment required to perform UBD operations is similar to one used in MPD, the only, but very vital difference, is that *Hydrocarbons Separation Equipment* required for separating multiphase flow anticipating in underbalanced drilling.

Dynamics of UBO

Figure 6 perfectly represents the UBD operations by showing how the BHP is changed during different stages of drilling process.

Part I – overbalanced drilling, represents non-reservoir section drilling. In the end of this part the gas injection begins, because Part II is anticipated to be reservoir.

Part II – underbalanced drilling.

Part III – pipe connection, the absence of circulation lead to decreasing of BHP, and that lead to increased influx volumes, so BHP will decreased even more, approaching to collapse pressure. That is why the connection time in UBD operations should be as short as possible.

Part IV – connection is finish, well flow causing transient pressure build up. [2]

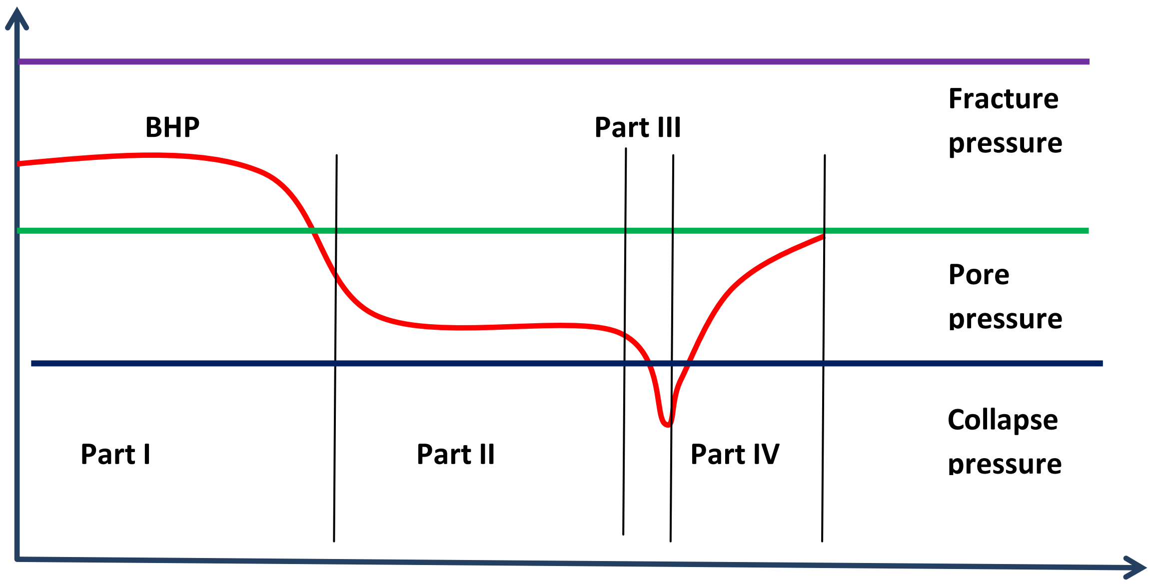

Figure 8. Dynamics of Underbalanced Operations.

Well control considerations

The primary well control during UBD is achieved by flow and pressure control, instead of mud column that is used in conventional drilling. And BOP stack provide the secondary well control.

The flow control system consist of following components

- NRV incorporated at the BHA,
- flare system,
- UBD separator,
- UBD choke manifold (not to be confused with rig's well control choke manifold)
- UBD control device
- Drill pipe.

During UBO, closed loop volumes and pressure while drilling are constantly measured in order to provide precise control on BHP and return well flow.

One of the main purposes of well control during UBO is not to allow the well to become overbalanced.

There are several reasons for kick to occur during UBO, such as, but not limited to reservoir pressure and/or permeability higher, than anticipated, insufficient control on choke or/and injection parameters, ROP exceeding designed parameters. [15]

Bull heading

Bull heading is well kill operation that is conducted by pumping kill fluid on high flow rates into well either through tubing or annulus with intention to force well fluid back to the formation. The operation is applicable when H2S is anticipated or no influx migration is allowed. However, due to high flow rates, burst casing can occur. Another thing to be aware of is high possibility to fracture the formation, which will lead to mud loss increasing.

1.6. Benefits and concerns of using near- and under balanced techniques.

As any system or technology, MPD operations have several advantages and disadvantages. One of the main advantage is reduction of uncertainty and drilling cost because of:

- conventional drilling NPT problems, such as lost circulation, kicks, nuisance gas zones and differential sticking are avoided
- prolonged bit life and increased ROP, which leads to reduced NPT and cuts number of tripping;
- enabled access to potential assets and reservoirs previously believed to be undrillable;
- reduced number of casing strings and, in some cases, deepening casing set points;
- reduced health, safety and environmental effects and risks by controlling fluids and pressures at all times.
- Increased cement job quality.

However, MPD operations have several disadvantages to be aware of:

- MPD operations are more expensive compared to conventional drilling
- Lack of a well-established standards
- Level of personnel training need to be very high
- The complicity of operations is match higher than in conventional way of drilling.[2]

Advantages and Disadvantages of UBO

Performing of UBD operations associated with variety of positive features, among them are:

- Improved reservoir productivity
- avoided reservoir damage
- possibility to perform tests during drilling
- avoided drilling fluid losses
- increased ROP
- minimized drilling problems. [16]

There are also some concerns to be aware of:

- One of the main challenges is the wellbore stability
- drilling costs higher, compared to conventional
- possibility to have higher Torque and drag
- increased weight of the string due to reduced buoyancy. [2]

1.7. Conclusions and further motivation.

As it was shown above, MPD and UBO is a very sophisticated techniques, that gives variety of advantages, such as, but not limited to: better well control, decreased NPT, better cementing. However, this drilling techniques is associated with different procedures, requirements and higher level of engineering. Due to quite newness of MPD and UBO, kick can not be avoided, although it can be controlled much better. As far as worst case scenario for kick is a blowout, and blowout itself is the most severe situation, it was decided to perform a set of experiments with intention to research kick rising and bull heading more deeply.

2. Experimental Part.

The aim of the planned experimental work is to simulate a kick situation by means of creating a Taylor bubble in a vertical pipe. The first step is to establish sufficient downward flow, that simulates a bull heading operation.

The central part of experiment is to install a Ventury insert to observe bubble behavior when entering Ventury. Then it is planned to achieve the steady state between bubble moving upward and a downward flow in the region of increased flow velocity created by a Ventury. All experiments will be conducted on water and PAC mixtures with different polymer concentrations. A 120 FPS camera is going to be used during experiments with intention to catch Taylor Bubble behavior.

In order to achieve a theoretical basis for planned experimental work and get some ideas about experimental facility modification, a number of papers on experimental studies on Taylor Bubble behavior in vertical pipes were researched.

Paper [17] by A. H. Rabenjamanantsoa, Rune W. Time and Thomas Paz gives a perfect insight of a lab facility and measurements methodology that is going to be used. The main principles of pressure measuring and high speed camera using are presented together with LabView package explanation. But the main benefit is that planned experiments will be performed on exactly the same facility as was used at this paper.

A great work has been done by authors of [18], aimed to review all material about rising velocity of Taylor Bubbles in stagnant liquid published until 2003. Experiments has been done on 76,2 mm pipe filled with different stagnant fluids. It was shown that the wake part of TB becomes more uniformal with increasing of viscosity. Laboratory facility, described in paper gave a good idea of using a tank in the top of the tube.

The paper [19] focused on measuring the gas losses of TB that is kept stationary in downward liquid flow. Also the radial void fraction distribution below TB was measured. Conducted experiments implied changing of such parameters as turbulence level of the flow, the bubble length and a liquid flow rate. The strong relation was shown between flux entrainment and the presence of turbulence in film. A good insight of gas balance of a TB in a slug flow was given. The SLUG-facility used in experiments also gave some good ideas, such as a way to measure some gas fraction related parameters.

Paper [20] describes a set of experiments for individual TB in counter-current flow with the Re number varies from 100 up to 10000. Good results visualization and very interesting conclusions are presented. Among them, the higher sensitivity to surface tension and higher relative rise velocity of asymmetric bubbles compared to symmetric is shown.

After research taken on previous experience the full understanding of conducted experiment was obtained. First of all, although existing facility is quite good, it should be modified in order to create circulation system. Second step will be inserting Ventury. According to previous research on scientific literature about Taylor bubble behavior in a vertical pipes, the most important rheological parameters of counter-current liquids are density, viscosity and surface tension. So the rheological measurements should be conducted.

2.1. Facility overview and modification.

Existing facility was designed and made in 2013 by Kim I.M. Flatråker as a part of his master thesis in order to perform studies on Hydrodynamic Oscillations of Non-Newtonian fluids in a U-tube. [21].

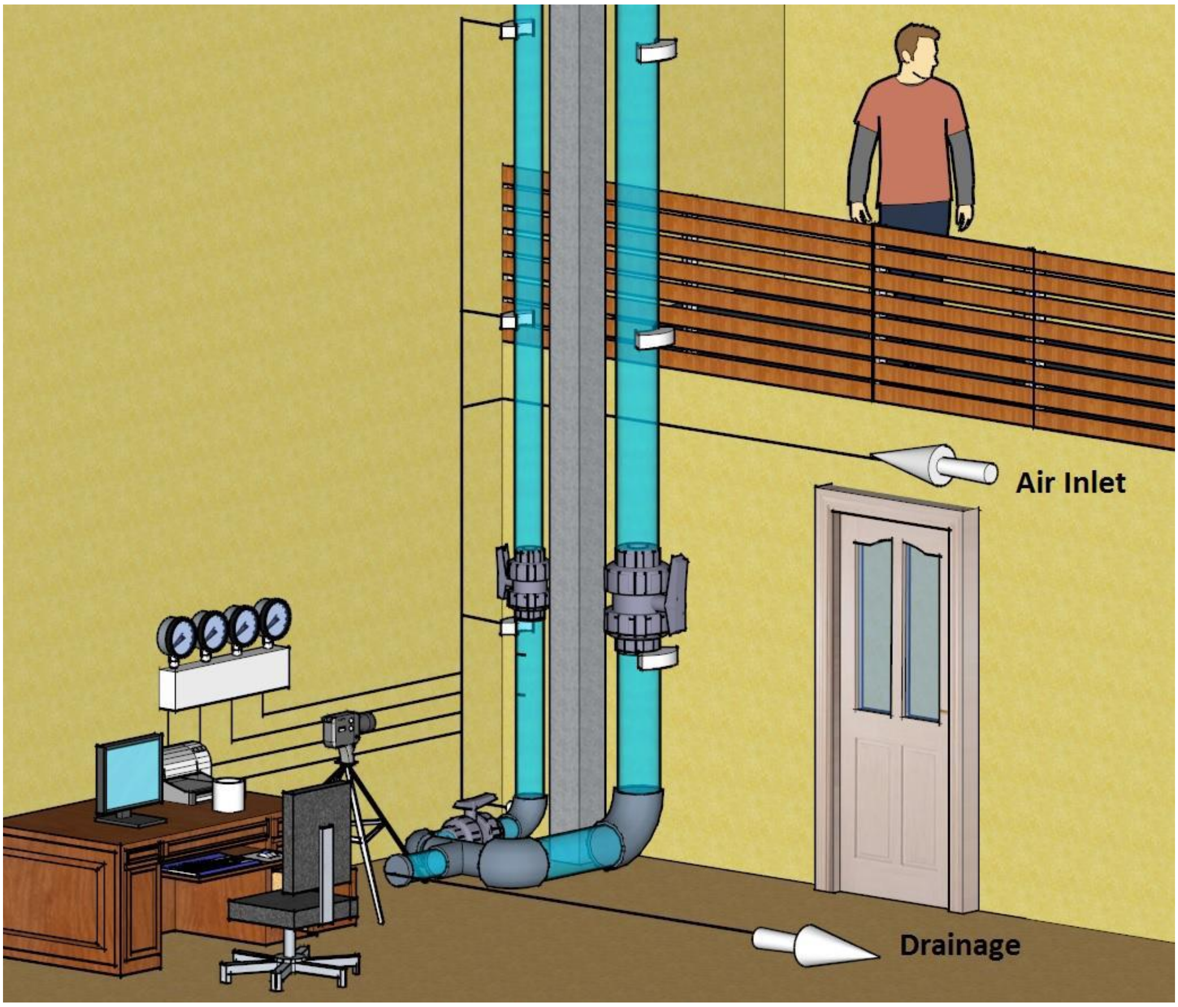

Figure 9. Given experimental facility. [21]

The experimental facility consisted of two vertical acrylic pipes connected in the bottom. Pipes are transparent and have diameters of 40mm and 80 mm. The high of pipes is 4,75 m, also both pipe are equipped with the valves approximately 1m from the bottom. Three pressure gauges are installed on both pipes 1 m from each other. The total volume is around 35 liters.

The main driver for modification was the need for establishing proper circulation system. The best way for creating the circulation is to use the pump. The pump selection should be driven by flow rate, required for create fluid velocity that will be sufficient enough for keep Taylor Bubble stationary in a Ventury throat, which have a diameter of 30 mm. So some calculations should be performed.

An universal correlation for the rise velocity of long gas bubbles in round pipe define as following [17]:

$$U_{TB} = K\sqrt{gD},$$

where,

U is bubble velocity

K is an empirical value about 0.351,

D is pipe diameter, and

g is acceleration due to gravity

$$U_{TB} = 0.351\sqrt{9.81 * 0.03} = 0.19\ m/s \text{ (in a Ventury throat)}$$

To achieve a stationary state between rising Taylor Bubble and counter-current flow, the downward liquid flow velocity should be the same as a rise velocity. To find the necessary pump rate, the flow rate should be defined:

$$Q = U_l \cdot A = U_l \cdot \frac{\pi \cdot D^2}{4},$$

Where U_l is a downward liquid velocity in a Ventury throat

$$Q = 0.311 \cdot A = 0.19 \cdot \frac{3.14 \cdot 0.03^2}{4} = 8.072\ l/m$$

After calculations was made, the Gear Pump was chosen. Pump Characteristics as following:

Table 1.

Flow Rate	14 l/min
Lift	20 m
Self Priming	1.5 m
Motor Supply	12 V DC
Fuse Size	10 A

In order to be able to regulate pump flow rate it was decided to use Switching Mode Power Supply.

After the pump was chosen, it was installed approximately 1 m below the top of aluminum support. The connection between pump and tubes was established by means of flexible pipes. One flexible pipe was subsided approximately 1m in 40mm pipe (to pump), while another (from pump) was put in the air gap in the top of 80mm pipe. It was noticed that water falling in 80mm pipe created bubbles and vortexes.

To eliminate (or, at least, decrease) this disturbances the decision was made to increase water level up to 0.25 m from top, to subside flexible pipe (from pump) 1 m below the top and to install a rubber plug in the top of 80mm pipe.

Figure 10. Gear pump.

The problem with bubbles was eliminated, instead of vortex. Moreover, a few experiments were taken and it was noticed, that vortexes become longer and more intense with increasing of flow rates.

It was assumed, that separating the flow will lead to decreasing the length of vortex propagation, so a decision was to install copper T-connector at the end of flexible pipe (from pump). Later experiments shown, that T-connector decreases the length of vortex propagation almost twice, but the aim is to eliminate them so it was decided to search for another options

- to improve the circulation system by using a tank
- to drill holes in T-connector intended to decrease jet and vortex effects by separating the flow
- to install vortex killers
- to install a centralizer on a flexible pipe (from pump)

Later it was decided to make two 12 mm holes from both sides of plastic T-connector with intend to separate the flow into 6 parts. The plastic T-connector with predrilled holes was successfully installed. It was some particles (probably leaves) left in the system, and previously decision was made not to clean the tubes before establishing the proper circulation, but use those particles as indicators of flow pattern instead.

During experiments with predrilled T-connector it was noticed that flow pattern become steady/vortex less around 0.5-0.75 m below the T-connector outlet. Later two sets of experiments were performed: the TB was released in 80 mm pipe with open end (case 1) and closed end (case 2). It was confirmed, that TB rising is more steady in case 2, because of significantly lower buoyancy (fluctuations) of water level, caused by the air gap. Also a suggestion was made to decrease the length of flexible pipe (from pump) at least twice (0,5 m from the top) with intend to increase the total length of test section.

It was also decided to rearrange the system by making the 40mm pipe closed and 80mm opened (vise versa of previous arrangement). Some ideas arisen were to make some kind of relief pipe by means of installing T-connector with valve on the flexible pipe (from pump) and make the system totally closed.

However, the flow circulation system was considered to be sufficient enough, so the only thing that needed to be done before inserting Ventury was to define the relation between voltage established and flow rate, provided by this voltage.

2.1.1. Flow rate – Voltage calibration for Gear Pump

Experimental facility was designed in order to define dependence between voltage and flow rate. The facility consisted of gear pump connected to Switching Mode Power Supply, two volume tanks and the weights.

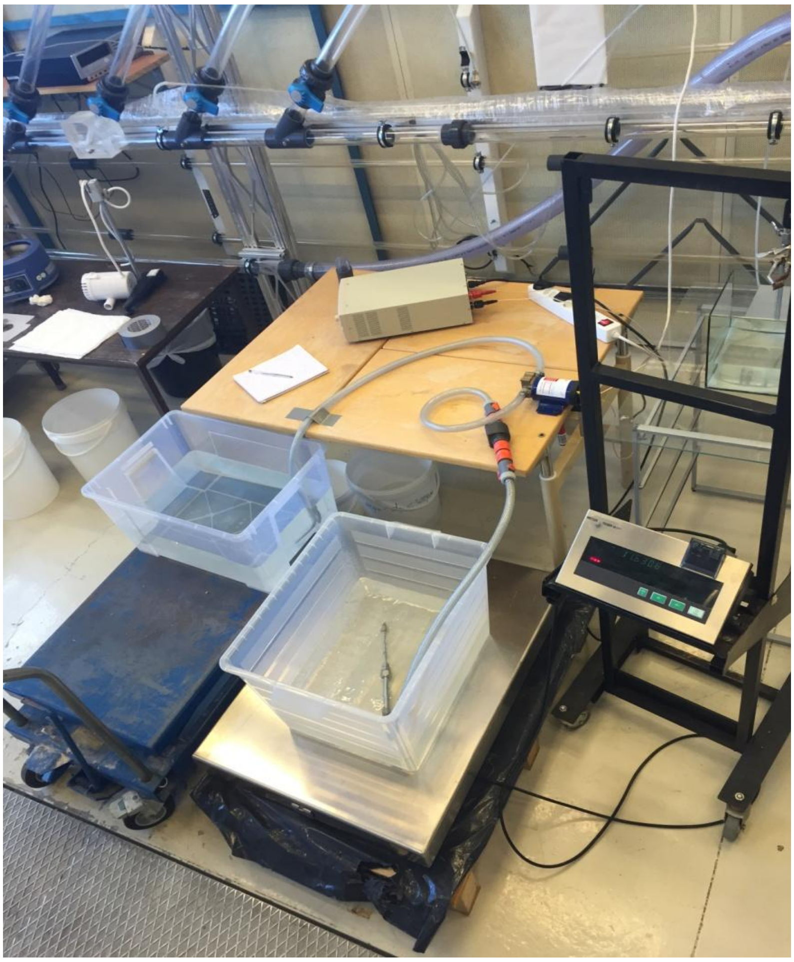

Figure 11. Designed facility for gear pump calibration.

The idea was to measure the time it takes for pump on given voltage to pump one kg of water. The measurements were made from 1 to 12 volt with step of 1 volt. In every step three measurements of time were taken. Results were gathered in the table that is presented below

After that, the visual voltage/flow rate dependence was made and the exponential trend line was added.

Table 2.

V	A	T1	T2	T3	T average	Q1	Q2	Q3	Q average
volt	amper	seconds	seconds	seconds	seconds	kg/min	kg/min	kg/min	kg/min
1	1.6	218.55	221.33	228.31	222.7300	0.2745	0.2711	0.2628	0.2694
2	2.3	110.44	110.49	110.93	110.6200	0.5433	0.5430	0.5409	0.5424
3	3.2	76	75.58	76.31	75.9633	0.7895	0.7939	0.7863	0.7899
4	4.1	57.76	57.78	57.7	57.7467	1.0388	1.0384	1.0399	1.0390
5	5.2	50.38	50.29	50.4	50.3567	1.1909	1.1931	1.1905	1.1915
6	6.3	46.16	46.03	45.86	46.0167	1.2998	1.3035	1.3083	1.3039
7	7.5	42.54	42.2	42.73	42.4900	1.4104	1.4218	1.4042	1.4121
8	8.6	40.2	40.25	39.85	40.1000	1.4925	1.4907	1.5056	1.4963
9	10.1	37.38	37.6	37.73	37.5700	1.6051	1.5957	1.5902	1.5970
10	11.3	35.33	35.73	35.98	35.6800	1.6983	1.6793	1.6676	1.6816
11	12.1	34.21	34.43	34.84	34.4933	1.7539	1.7427	1.7222	1.7395
12	13.2	33.19	33.54	33.36	33.3633	1.8078	1.7889	1.7986	1.7984

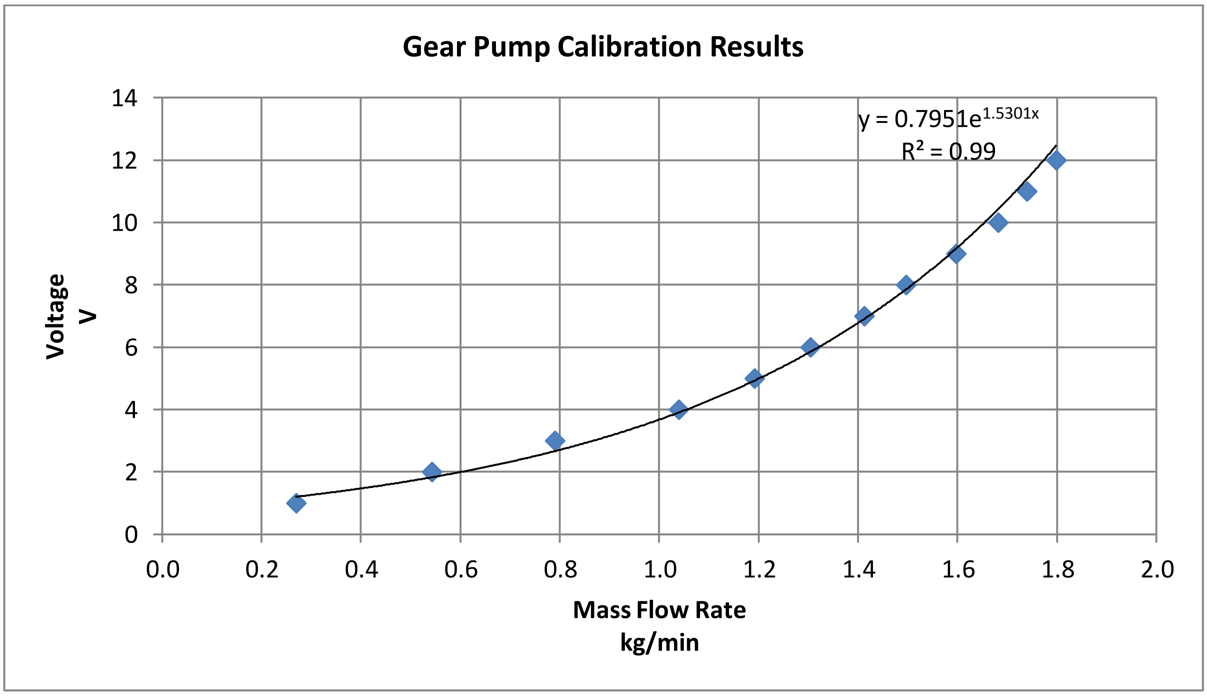

Figure 12. Gear Pump Calibration Results.

It was noticed, that for some reason, chosen pump does not provide the flow rate it should provide. That fail become a motivation for establish new pump system.

2.1.2. Flow rate – Voltage calibration for Bilge Pump

A new, powerful Bilge pump was bought. Pump characteristics presented in Table 3:

Table 3.

Flow Rate	95 l/min
Lift	4 m
Motor Supply	12 V DC
Fuse Size	20 A

In order to not make the same mistake for second time it was decided to perform Voltage/Flow rate pump calibration first.

Figure 13. Bilge Pump.

Calibration was performed on different facility but with the same pump and power supply. There were two set of experiments: for water and for PAC mixture with concentration of polymer 4 g per l.

Water

Flow rate measurements was taken by magnetic mass flow meter on the Voltage 1 to 12 volt with step 0,5 V. Flow rate measurements were taken every 6 seconds, after establishing of steady flow the voltage was increased. Obviously, it takes more time for lower flow rates to become steady. Results are presented in Figure 14.

As far as Water have density of 1000 kg/m^3, then Mass Flow Rate of kg/s equals to the same value in l/s.

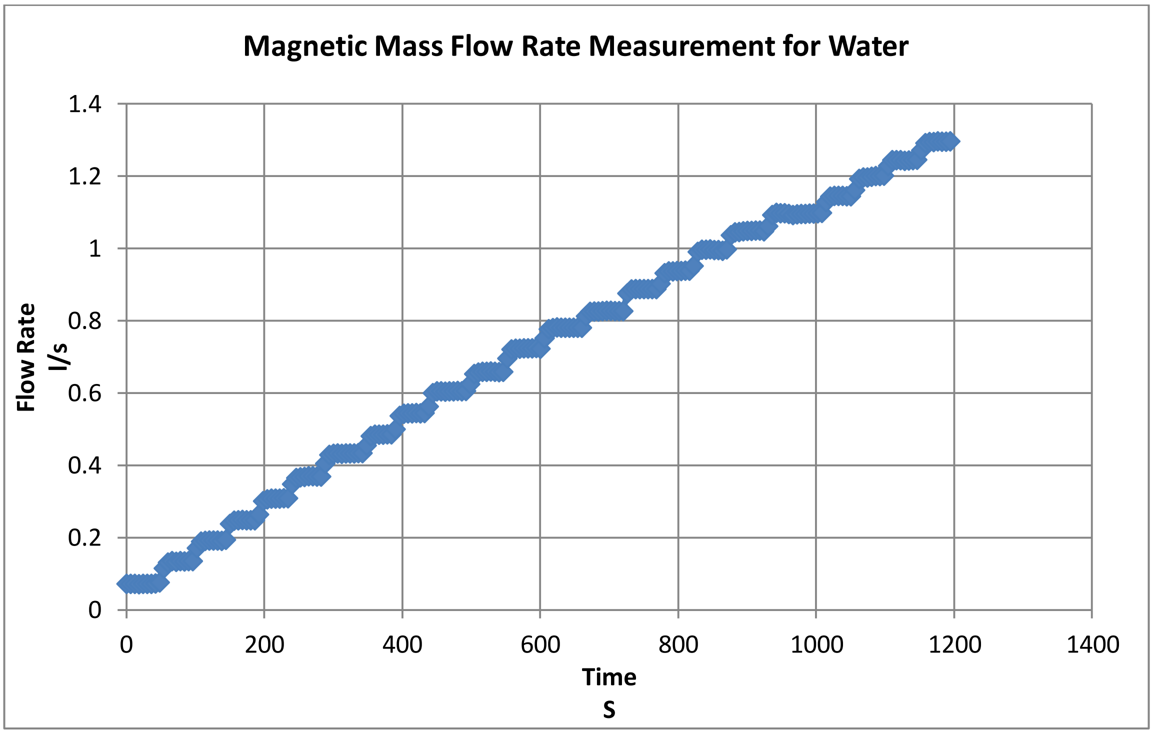

Figure 14. Magnetic Mass Flow Rate Measurement for Water.

The average values were taken together with Standard Deviation in visualization of voltage/flow rate dependence.

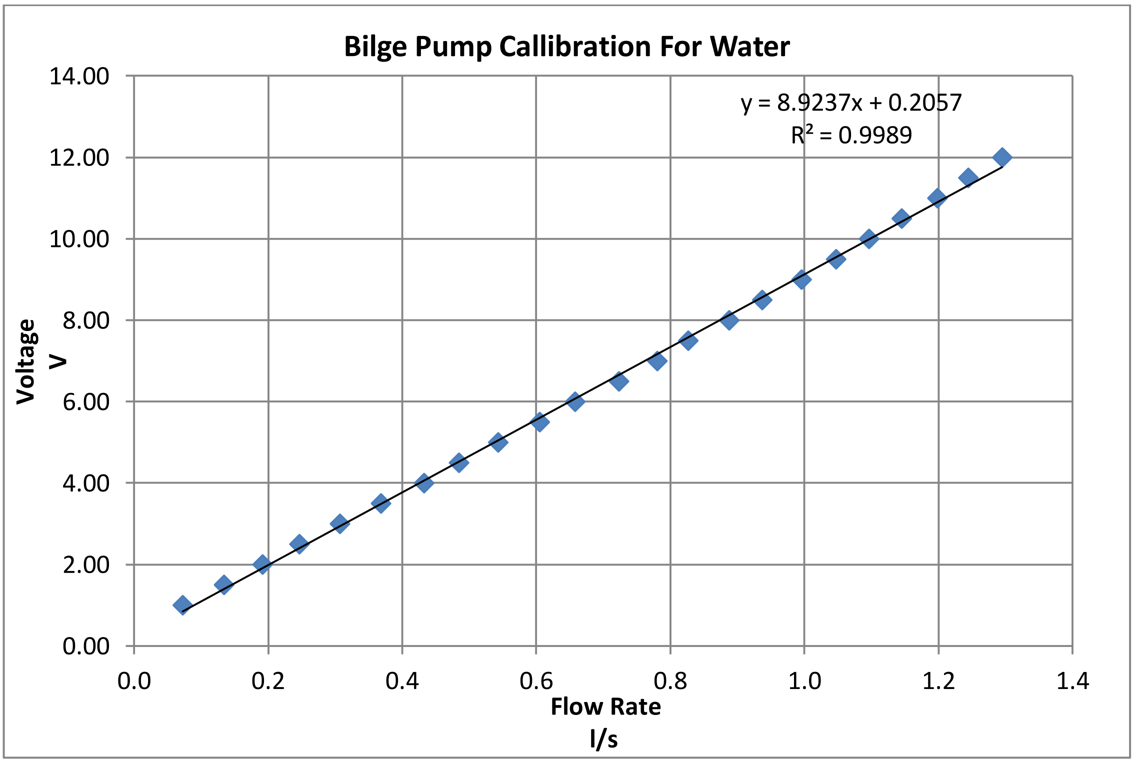

Figure 15. Bilge Pump Calibration For Water.

As one can see, this time the dependence is almost perfectly linear and flow rates are sufficient.

PAC mixture with polymer concentration of 4 g/l.

The same procedure was done in system filled with PAC mixture. Unfortunately, the rheological properties of the fluid put some limitation on measurements: there was no flow below 3,5 Volt and volume of system was too small to get stable results above 10 Volt.

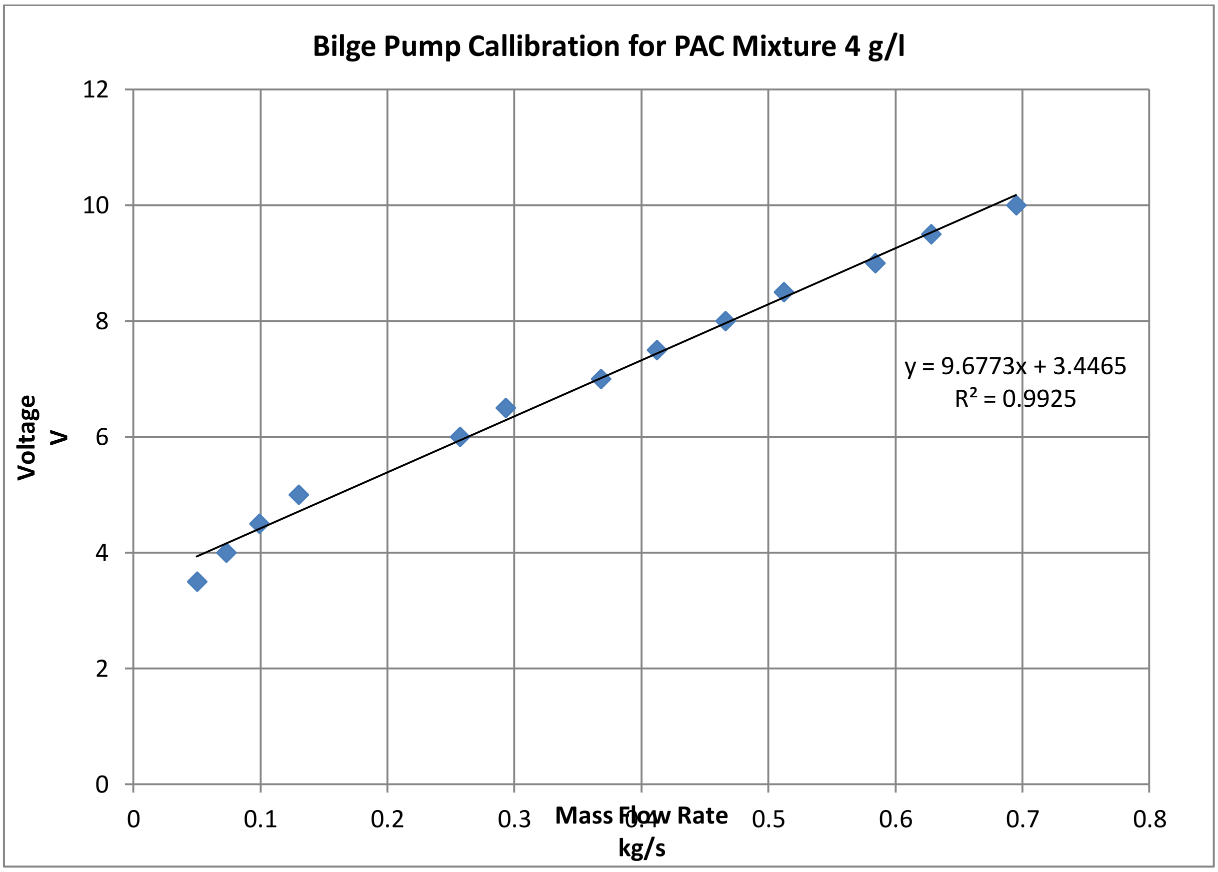

Figure 16. Bilge Pump Calibration For 4 g/l PAC Mixture.

It was decided to use Voltage values as a reference in all planned experiments, because it is much easier to deal with those numbers. So in order to define relevant flow rate one can easily refer to Figures 15 and 16.

2.1.3. Modification of the top part of facility.

The submersible bilge pump was powerful enough to provide required Flow rate but unfortunately could not deliver fluids to required height. That is why a decision was made to install a 25 liter buffer tank close to the top of the tube system, put the pump in that tank and create the connection between 40 mm pipe and tank. In order to deliver fluids from pump to 80mm tube, a flexible pipe was planned to be used.

All the necessary arrangements were made prior to a buffer tank installation. A question arose about the way of connection between 40mm tube and a tank. Two options were estimated: T and Y connector. Finally, it was chosen to use T connector, because it gives advantages of using only 90 degrees elbow-to-pipe connections, so the system will have more flexibility and all the connecting pipes will lay in two perpendicular plates. After installation of T connector and building up a pipe connection system, the stability of whole tank-u pipe-t connector section was estimated. It was noticed that u-pipe may be the weakest point, so a decision was made to install a support for this section.

Decision was made to install a valve between T-connector and U-tube in order to obtain additional tool of flow regulation. When it was made, the whole experimental facility was filled with water prior to integrity testing. Unfortunately, a few leakages were found, so some of connections were re-glued.

Next step was to design a floater for submersible pump. Two options were accessed: closed flexible pipe filled with air and plastic foam. The idea of flexible pipe is easy to implement, but floating capacity may not be enough. On the other hand, floating capacity of plastic foam is very high, but material itself is hard to work with.

However, there was an another option – not to use floaters, but make an additional protection for pump cables and place the pump on the bottom of a tank. So three layers of silicone glue was put on the place where cable connects to the pump.

After this, pump was placed in tank and checking of flow circulation system starts. The flow rates that can be delivered by a new pump were significantly higher, so the vortex propagation was noticed to be very long. It was assumed that vortex problem is caused by two main reasons – lack of vortex killer and uncentralized flexible pipe (from pump).

The whole new system was designed in order to eliminate issues stated before. Figure 17 shows the system.

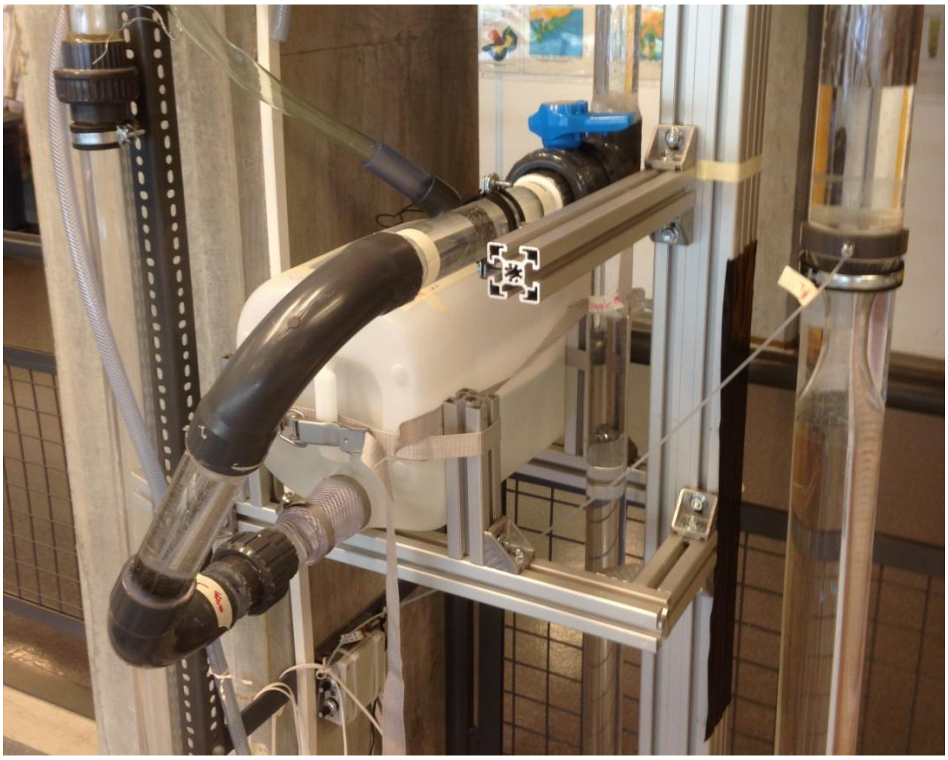

Figure 17. Top Part of the system.

System consists of two VK, connected by protected wires (in order not to let any corrosion affect on experimental results). VK are made from aluminum honeycomb and a tape is put on them in order to protect inner wall of acrylic pipe from scratching. The length of the VK is 80mm. The length between VK is 185 mm.

Upper VK connected directly to flexible pipe outlet so it also acts as a centralizer. The testing of designed system had shown very good results and lack of vortexes. Also, testing this system with adding bubbles helped to define a place where the Ventury should be placed. It was noticed, that there is a point somewhere around 20-50 cm (depending on flow rate) below the lower VK, where bubbles are gathered without any tendency to raise above. So it was decided to install Ventury 135 mm below lowest VK.

Volume definition

Total Volume of the system was defined simply by filling dry system with water. Finally the Volume was estimated to be 45 liters.

Ventury insert

The ventury was made from acrylic glass and have a length of 235 mm, inner diameter of 30mm in the central part and 77mm on the edges. The outer diameter is very close to inner diameter of the pipe, so Ventury can be held without any additional fixers. However, in order to provide sufficient level of safety and to keep Ventury from fallen, it was decided to apply some pressure on tubing wall in the place where Venturi was insert by means of clams.

Figure 18. Ventury insert and Vortex Killer System.

2.2. Experiment

After successful experimental facility modification and pump calibration, time has come to perform planned experimental sets. It was decided to conduct 5 sets of experiments, each of them includes frictional pressure loss definition for system with and without bubble together with rheological experiments. More precise description could be found in a following chapter.

2.2.1. Experimental methodology description

As it was mention above, all conducted experiments was divided into 5 sets based on fluid tested. They are:

1. Water
2. PAC mixture with polymer concentration 4 g/l
3. PAC mixture with polymer concentration 3 g/l
4. PAC mixture with polymer concentration 2 g/l
5. PAC mixture with polymer concentration 1 g/l

For every set following experiments were conducted:

1. Frictional pressure loss definition for tested fluid system;
2. Frictional pressure loss definition for tested fluid system with bubble introduced. Also high FPS video was taken at this step;
3. Rheological tests, including density, viscosity and surface tension definition.

PAC (polyanionic cellulose) is a polymer that creates shear thinning Non-Newtonian fluid when mixing with water. In order to make a set of experiments on PAC mixtures with different polymer concentrations a 45 liters of PAC mixture with concentration 4 g per l was prepared 72 hours before planned experiment. Usually it requires 48 hours for PAC mixture to become wetted. In order to decrease concentration of mixture for every next set of experiment a simple procedure was taken:

First, pre-calculated amount of mixture was taken out from facility and replaced with the same amount of water. Then, pumping was initiated for 30 minutes in order to mix water with polymer mixture.

Frictional pressure loss definition for tested fluid system

The experimental definition of pressure losses was conducted in a following way:

Experimental facility is equipped with pressure sensors. One is located just below the valve in 80 mm tube and represents the absolute pressure or a pressure head. Two sensors are located below the valve in 40 mm tube with height difference between them equals to 1m. those sensors measure pressure difference in this part of 40 mm tube. Two sensors are located in 80mm tube 1 and 2 m below Ventury top and measure pressure difference for 1 m height.

First, pressure readings were performed in system filled with water but without flowing in order to calibrate the system by insuring that delta P values for 40 mm and 80mm tubes equals to zero. That mean, that delta P values obtained during experiment will represent frictional pressure losses in relevant parts of 40 mm and 80 mm tubes.

Then, pressure readings were taken on circulated system for different flow rates, represented by different voltages regulated on Power Supply. The voltage range and voltage steps defined for each fluid system empirically during preliminary testing.

Frictional pressure loss definition for tested fluid system with bubble introduced

Next step is to introduce the Taylor Bubble in circulating system and perform pressure readings as in previous chapter. In this part voltage range and steps were also defined empirically during preliminary testing. For each step a high FPS video was taken for region of approximately 1m length of 80 mm tube from Ventury top to higher pressure sensor, which, as it was mentioned, is located 1m below Ventury top. The video is taken with intention to observe TB behavior for different flow rates.

Rheological tests

The third step was to define the rheological properties of fluid tested.

Density

The density was measured on Anton Paar DMA 4500 apparatus. This facility characterized by wide range of temperature and viscosity measurements possibility together with incredible accuracy of measurements and correction of viscosity caused errors. The accuracy of temperature measurements is achieved by two integrated platinum thermometers.[22]

For every fluid system density definition was conducted according to manual in a following way:

First, apparatus was flashed with BI water and calibrated and only after that the fluid sample was tested. All fluids were tested at temperature equals to 20C.

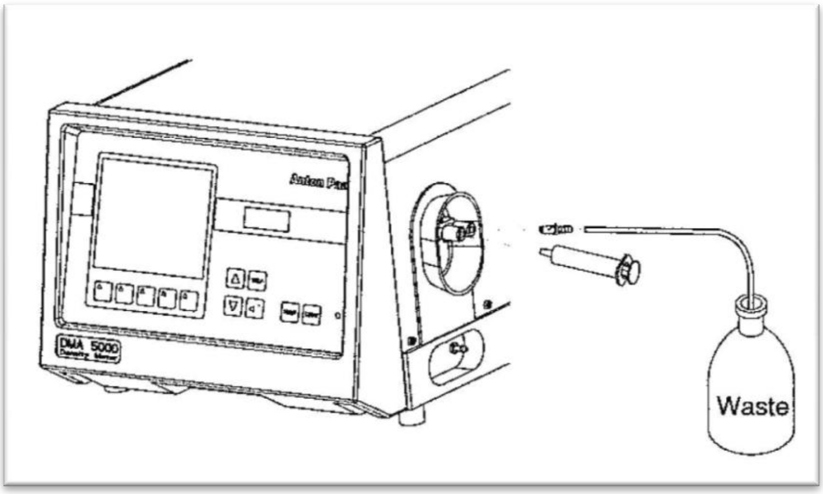

Figure 19. The Anton Paar DMA-4500 Density Meter. Anton Paar DMA-4500.[22]

Viscosity

Viscosity was defined by using Anton Paar Modular compact Rheometer MCR 302. [23]

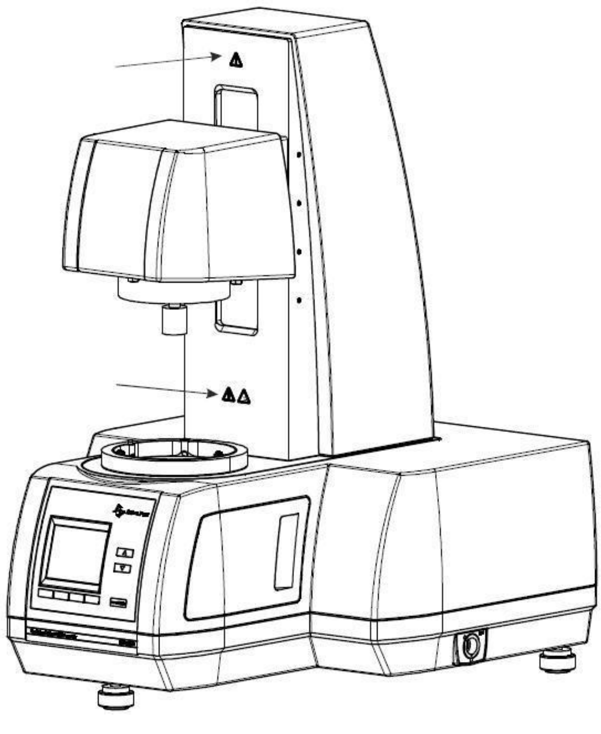

Figure 20. The Anton Paar MCR-302 Viscosity Meter . [23]

This apparatus is a perfect example of sophisticated machinery, that provide wide range of rotational and oscillatory rheological tests.

For all tested fluids a viscosity test were conducted with the plate-cone (CP50-1) modification, which characterize by separation distance of 0.096mm. Temperature was established to be 20 deg.

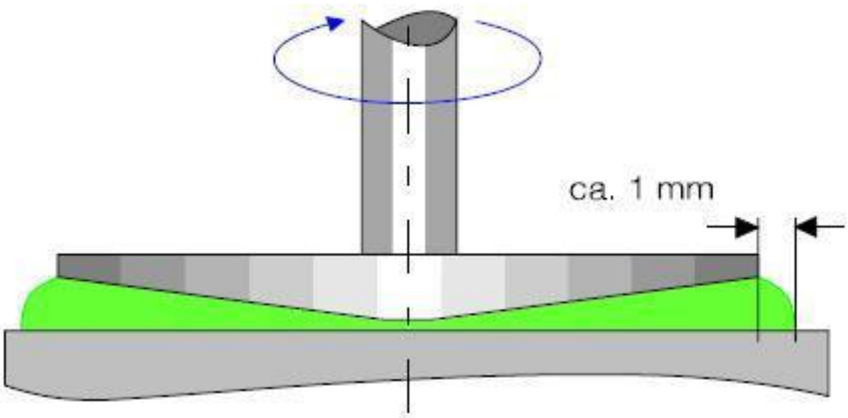

Figure 21: The Plate-Cone (CP50-1) configuration in its measuring position with ideal amount of sample present . [23]

In order to observe anticipated hysteresis the measurements were established to be taken from shear rate of 0,01 to 1000 s-1 and back. 26 steps were taken both directions.

Surface tension

The surface tension measurements made by so called “Platinum Ring Method”. In this method the ring subsided to measured fluid and then slowly pulled up by accurate rotation of white plastic dial. In some critical point ring tears the liquid film. That point represents the surface tension in mN/m. All measurements conducted in room with temperature equals to 20C. Three measurements were made for each fluid with intention to improve the accuracy of measurements.

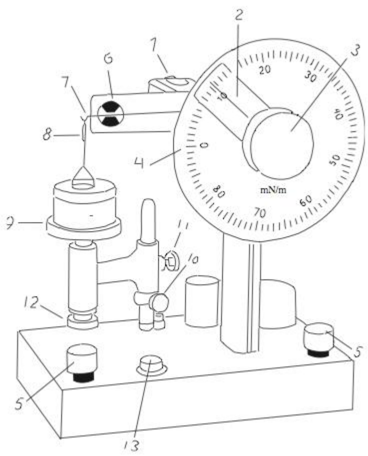

Figure 22. Facility for Surface Tension Measurement.

According to manual, there are two correlation factors for obtained value than need to be calculated:

1. **Temperature correlation factor (C)** can be calculated in a following way:

$$C = \frac{Surface\ tension\ of\ distilled\ water\ at\ 20°C}{Measured\ surface\ tension\ of\ distilled\ water} = \frac{72.75}{70.5} = 1.032$$

Surface tension of distillated water was taken from manual as a reference value, measured surface tension of distillated water was obtained directly by measurements.

2. **Correction factor for ring and fluid that is lifted**

The F factor can be defined as following:

$$F = \left\{0{,}725 + \sqrt{\frac{0{,}01452 \cdot \sigma^*}{\frac{U^2}{4} \cdot (\rho_2 - \rho_1)} + 0{,}04534 - \frac{1{,}679}{\frac{R}{r}}}\right\} \cdot 1{,}7$$

where

R = mean radius of platinum ring = 0,9549 cm

r = platinum string cross-section = 0,0185 cm

$U = 4 \cdot \pi \cdot R$ = 0,0119996 cm

ρ_1 = Density of the lightest phase

ρ_2 = Density of the heaviest liquid phase

The final value for surface tension can be defined as following:

$$\sigma = \sigma^* \cdot C \cdot F$$

where

σ = real value for surface tension

σ^* = measured value for surface tension

C = Temperature correlation factor

F = Correction factor for ring and fluid that is lifted.

2.2.2 Experiment results and discussion

2.2.2.1 Water

Pressure losses with no bubble

After it was checked, that both delta P sensors reed zero value in system without flow, the circulation was initiated and pressure readings were taken for flow rates relative to voltages from 5 to 12 volt with the step equal to 1 volt.

For each voltage around 6000 measurements of frictional pressure loss were taken with the rate 100 measurements per second. Then average value was taken for each voltage and Standard Deviation value was calculated. Results could be found in Table 4 and Figure *. Unfortunaly, values for 80mm tube were too small to be red.

Table 4.

	40 mm Tube	
Voltage	Average Frictional Pressure Losses	Standard Deviation
V	mBar	mBar
5	0.182402836	0.056730904
6	0.330856547	0.049749383
7	0.528868891	0.069593717
8	0.765835696	0.050203811
9	1.015182652	0.063470841
10	1.272390325	0.072856726
11	1.504058882	0.074067073
12	1.803321268	0.075664545

As one can see from Figure 23, there is clearly linear dependence between flow rates represented by voltages and frictional pressure losses.

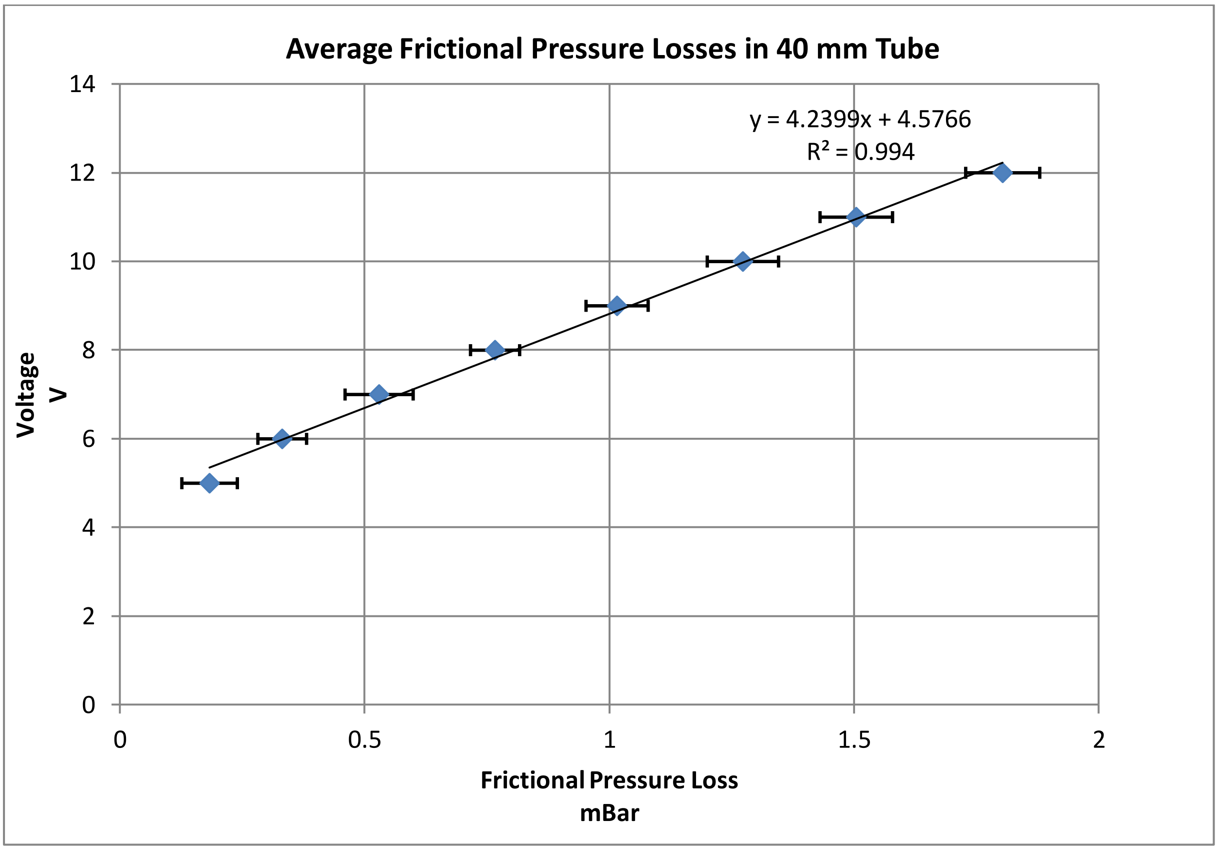

Figure 23. Average Frictional Pressure Losses in 40 mm Tube.

Pressure losses with bubble

During conduction of preliminary experiment with bubbles it was noticed that propagation of smaller bubble below TB is changing with time, so it was decided to perform the experiment in a following way:

After obtaining a steady flow at 6v the bubble was introduced. Then, pressure readings was conducted for 5 minutes for each voltage from 6v to 12 v and back with a step of 1 volt. Pressure readings were taken every second.

Figure 24 represents experimental results. It should be noticed here, that it takes approximately 30 seconds in order for voltage to be changed for 1 volt and for flow to be established (e.g. for fluid level in both 40 mm and 80 m tubes to be established). So this peaks in Figure 24 represents the time period of changing and establishing of the flow.

A 120 fps video was taken with intention to obtain a visual understanding of bubble behavior. The difference in bubble propagation could be found in Appendix 1.

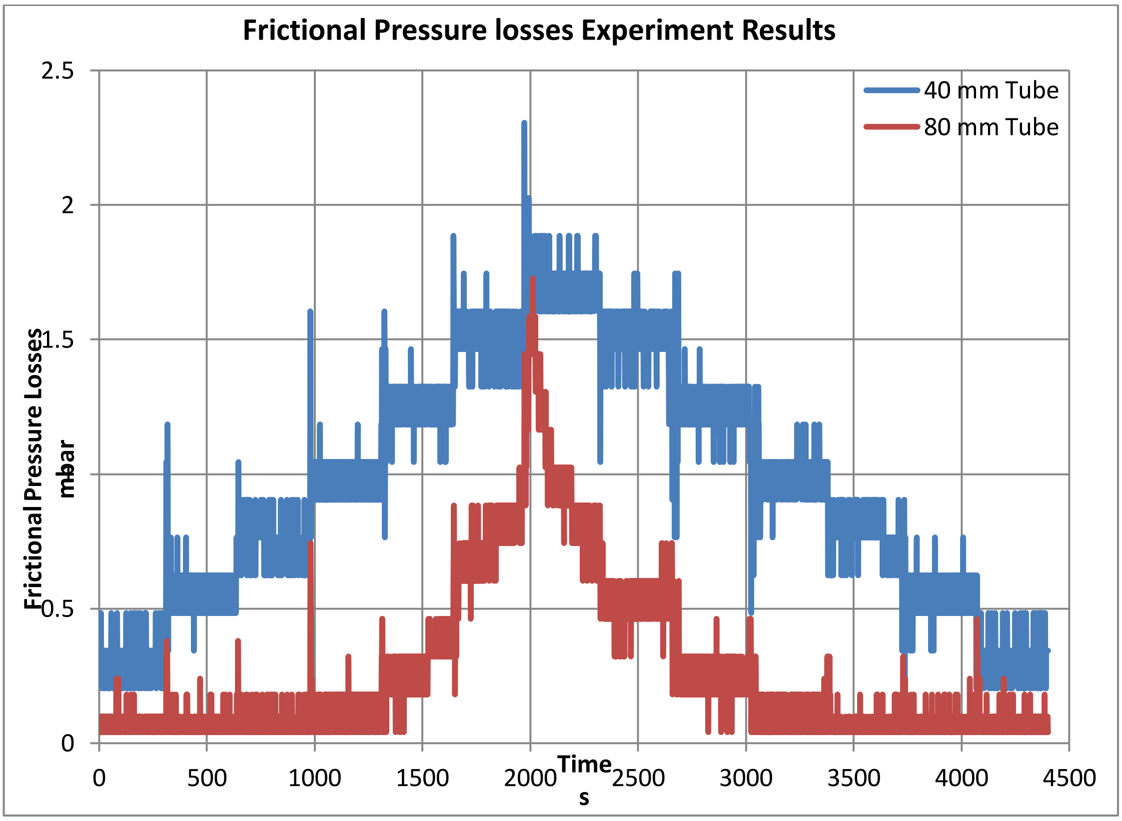

Figure 24. Frictional Pressure losses Experiment Results.

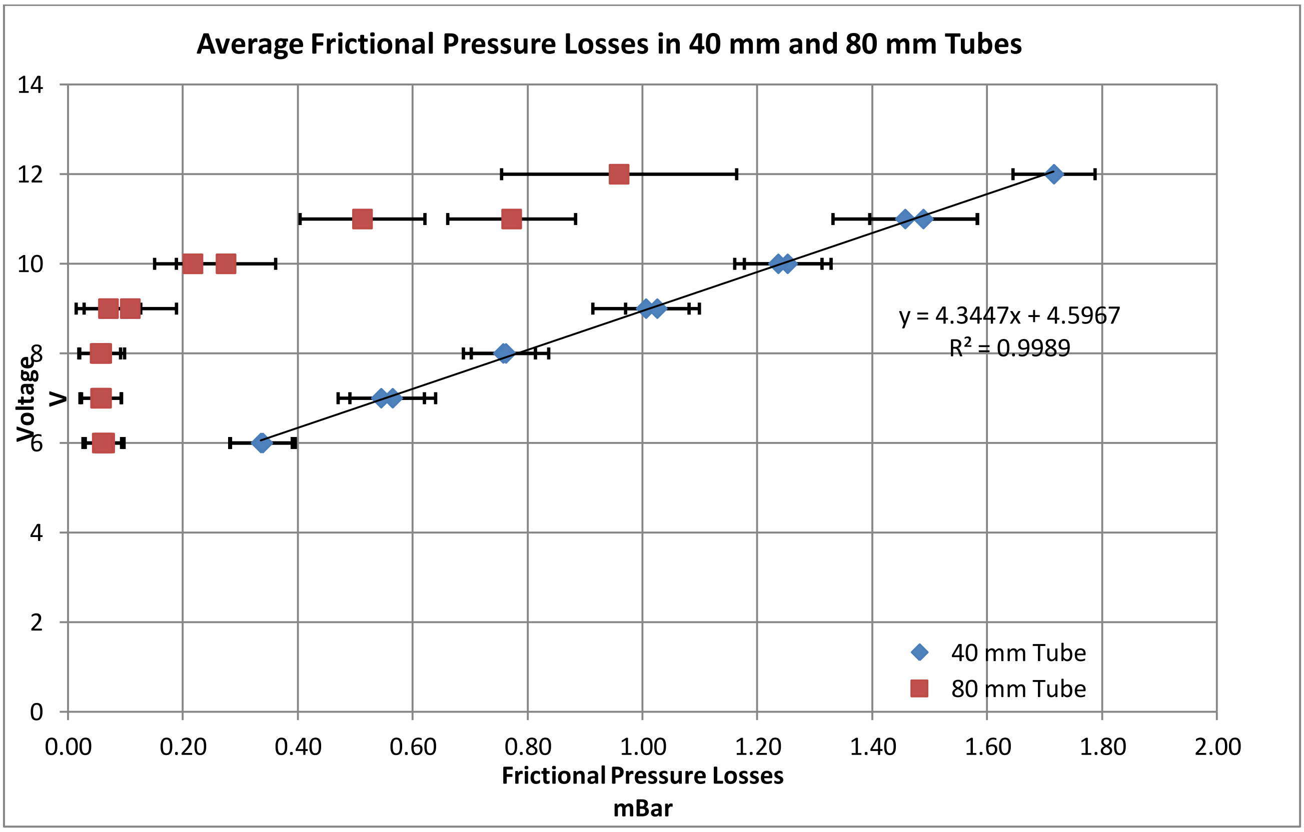

Figure 25. Average Frictional Pressure Losses in 40 mm and 80 mm Tubes.

The average value and standard deviation was calculated for each voltage. Results are presented in Table 5 and Figure 25.

Table 5.

	40 mm Tube		80 mm Tube	
Voltage	Average Frictional Pressure Losses	Standard Deviation	Average Frictional Pressure Losses	Standard Deviation
V	mBar	mBar	mBar	mBar
6	0.33553	0.05440	0.06333	0.03377
7	0.56487	0.07460	0.05627	0.03583
8	0.75739	0.05587	0.05825	0.03982
9	1.00586	0.09275	0.10804	0.08040
10	1.25237	0.07548	0.27464	0.08640
11	1.48866	0.09351	0.77186	0.11129
12	1.71591	0.07143	0.95890	0.20462
11	1.45704	0.12584	0.51221	0.10864
10	1.23609	0.07596	0.21708	0.06674
9	1.02540	0.05523	0.06999	0.05619
8	0.76207	0.07425	0.05553	0.03555
7	0.54487	0.07509	0.05795	0.03482
6	0.33881	0.05642	0.05926	0.03358

With increasing of flow rates Taylor Bubble becomes Asymmetric and smaller bubbles tears apart from it, creating a wake of certain length. There are bubbles of different diameters in this wake, and the smallest one, as they have the smallest rice velocity are forced to move downwards by counter-current liquid.

As one can see from Appendix 1, Taylor Bubble brakes on flow rates equal to 11 voltage, the wake length is approximately equal for 7, 8 and 9 volt, at 10 volt the region below wake consisted of smallest bubbles become distinctive on pressure readings. In 11 volt flow rates the wake merge smallest bubble region and propagates in length. In flow rates equal to 12 volt there only few bubbles below Ventury, while most of bubbles were forced downwards.

When flow rate gradually decreased, bubbles raised back towards Ventury with clear tendency to decreasing the length of the wake with decreasing flow rate. It was interesting to observe that although TB was broken at 11 volt, it gathered back only in 6 volt. Pressure losses for 40 mm tube shows perfect linear trend, that means there was no significant bubbles breakthrough in 40 mm tube.

2.2.2.2 PAC mixture with concentration 4 g /l.

Pressure losses with no bubble

Pressure loss readings was conducted for flow rates equal to voltage from 6 to 10 volt with a step of 0,5 volt. For each voltage more than 5000 measurements were taken with 100 measurements per second rate. Then average frictional pressure losses and standard deviation were calculated. Results are presented in Table 6 and Figure 26.

Table 6.

	40 mm Tube		80 mm Tube	
Voltage	Average Frictional Pressure Losses	Standard Deviation	Average Frictional Pressure Losses	Standard Deviation
V	mBar	mBar	mBar	mBar
6	1.04280	0.04304	0.10688	0.03801
6.5	2.17287	0.04749	0.06101	0.03185
7	3.13217	0.05106	0.07381	0.05935
7.5	3.98157	0.05438	0.18411	0.04535
8	4.82128	0.04778	0.29715	0.05970
8.5	5.47069	0.07412	0.35959	0.06649
9	6.18961	0.06988	0.45607	0.04603
9.5	6.65414	0.04944	0.48956	0.06110
10	7.24317	0.06357	0.59525	0.04671

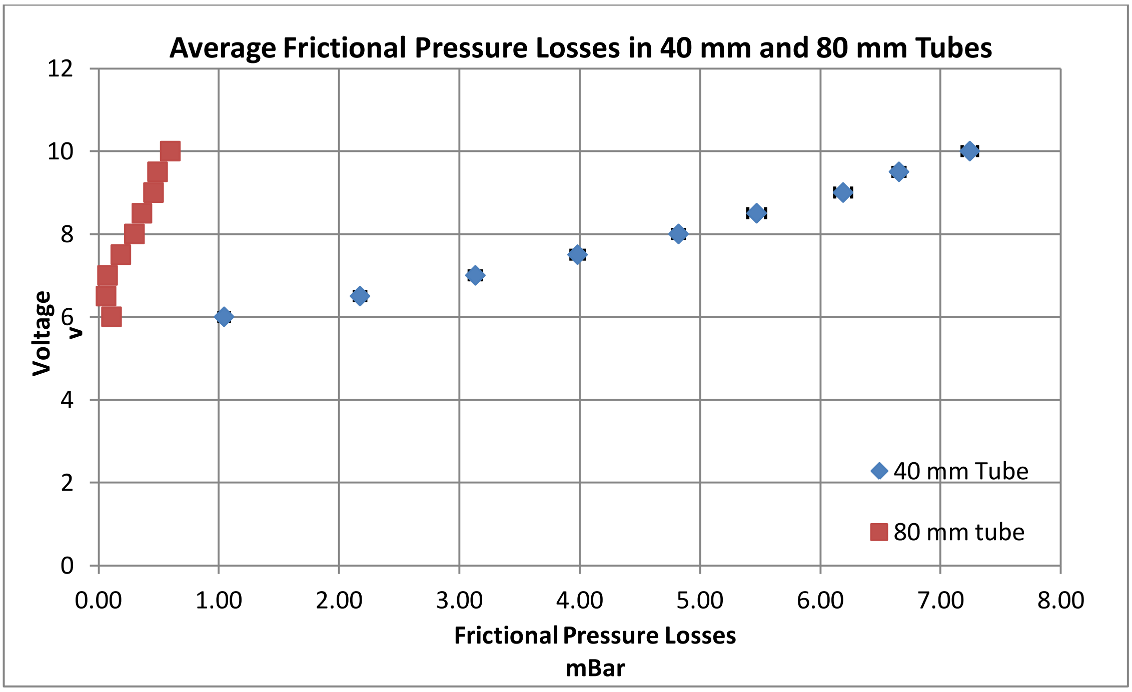

Figure 26. Average Frictional Pressure Losses in 40 mm and 80 mm Tubes.

Pressure losses with bubble

Taylor Bubble was introduced in flow rate equal to 7 volt. Then voltage was increased to 10 volt with a step of 0,5 volt. For each voltage more than 5000 measurements were taken with 10 measurements per second rate. Then average frictional pressure losses and standard deviation were calculated. Results are presented in Table 7 and Figure 27.

Table 7.

	40 mm Tube		80 mm Tube	
Voltage	Average Frictional Pressure Losses	Standard Deviation	Average Frictional Pressure Losses	Standard Deviation
V	mBar	mBar	mBar	mBar
7	3.14217	0.05723	0.08131	0.06368
7.5	3.97124	0.06222	0.18441	0.04541
8	4.81913	0.05005	0.29934	0.05889
8.5	5.46612	0.07480	0.35863	0.06583
9	6.15049	0.10088	0.45610	0.04599
9.5	6.63589	0.07131	0.49159	0.06235
10	7.21638	0.09220	0.59466	0.04606

Visual observations of Taylor Bubble behavior shows totally different picture compared to water filled system. There is no bubbles tearing away from Taylor bubble. The asymmetry of TB increasing with increasing of flow rates.

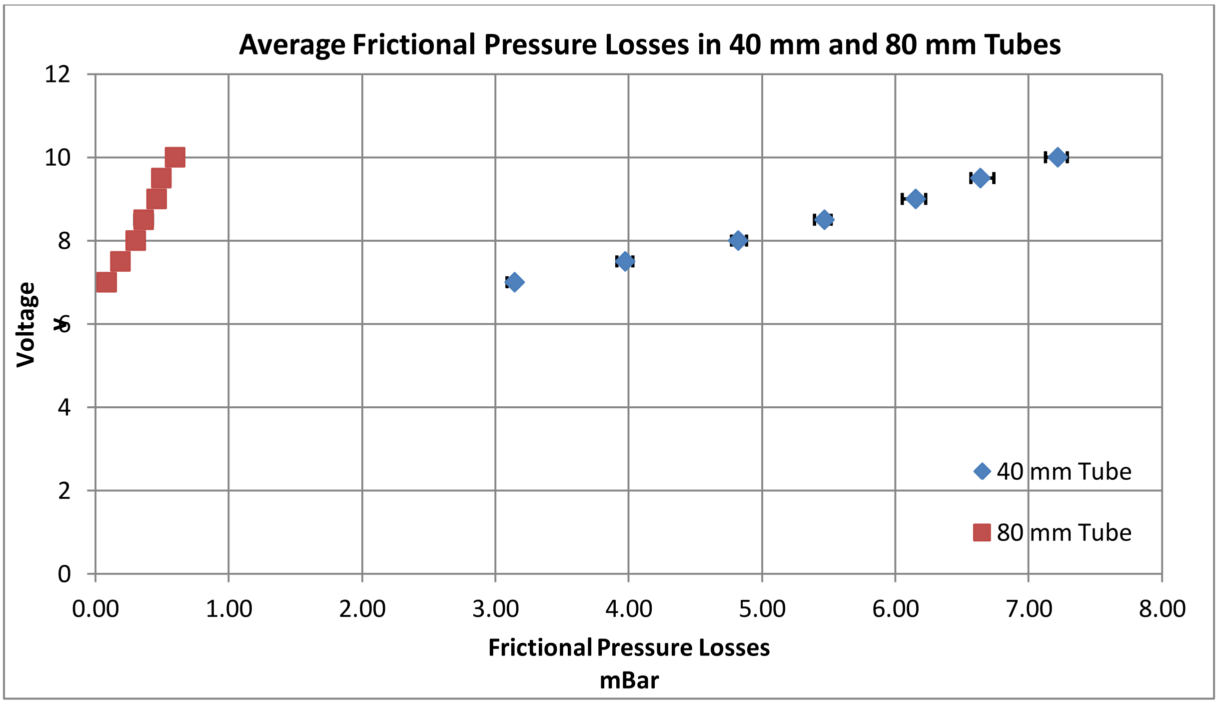

Figure 27. Average Frictional Pressure Losses in 40 mm and 80 mm Tubes.

An interesting phenomenon was observed. The downwards flow from Ventury throat tends to create a sort of channel. The channel cold be also referred as a slope and this slope is increase with increasing of flow rate. That is related to Shear Thinning properties of PAC mixture. Increasing of shear stress in Ventury throat causing the field of decreased viscosity. The overall visual representation of Taylor Bubble behavior could be found in Appendix 1

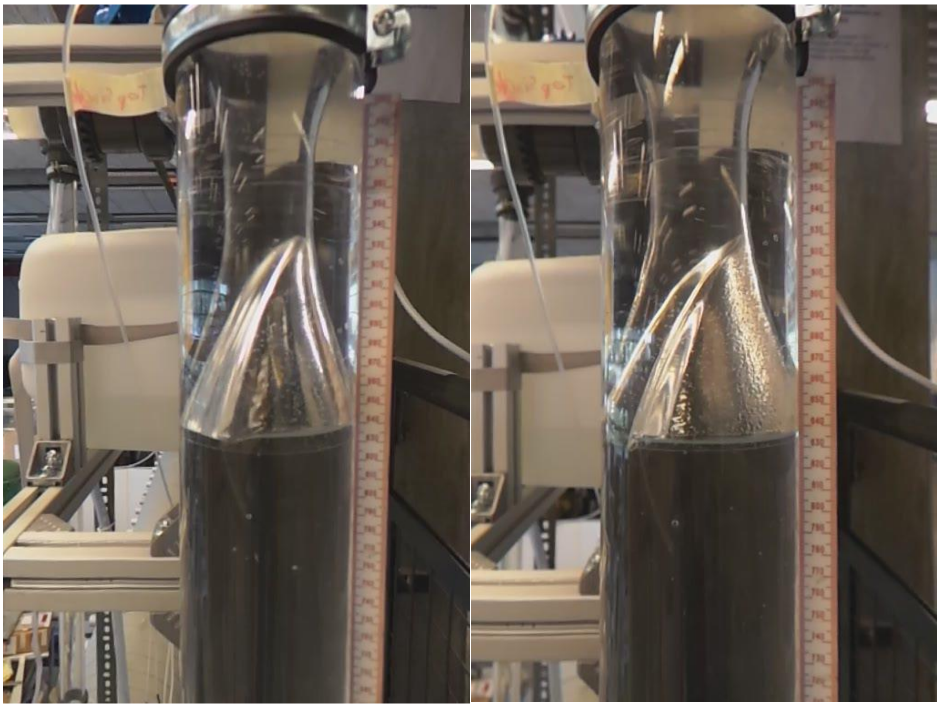

Figure 28. Bubble behavior in a Ventury Throat for flow rates related to 7v (left) and 9v (right).

2.2.2.3. PAC mixture with concentration 3 g /l.

Pressure losses with no bubble

Pressure loss readings were conducted for flow rates equal to voltage from 6 to 12 volt with a step of 1 volt. For each voltage more than 5000 measurements were taken with 100 measurements per second rate. Then average frictional pressure losses and standard deviation were calculated. Results are presented in Table 7 and Figure 29.

Table 7.

	40 mm Tube		80 mm Tube	
Voltage	Average Frictional Pressure Losses	Standard Deviation	Average Frictional Pressure Losses	Standard Deviation
V	mBar	mBar	mBar	mBar
6	1.04540	0.04299	0.08680	0.02988
7	2.55266	0.06550	0.06550	0.05319
8	3.80464	0.06993	0.19274	0.04932
9	4.67375	0.05324	0.30126	0.05673
10	5.56996	0.06844	0.33191	0.04825
11	6.36569	0.04362	0.48459	0.05639
12	7.07067	0.04425	0.58618	0.05414

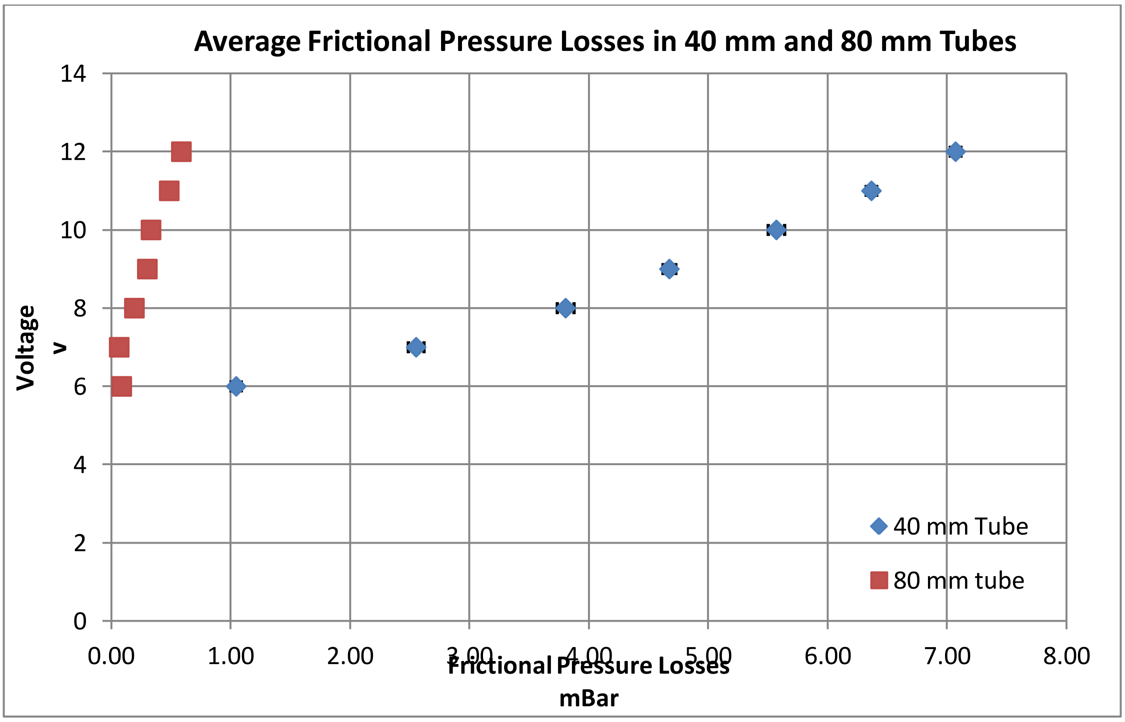

Figure 29. Average Frictional Pressure Losses in 40 mm and 80 mm Tubes.

Pressure losses with bubble

Taylor Bubble was introduced in flow rate equal to 7 volt. Then voltage was increased to 12 volt with a step of 1 volt. For each voltage more than 5000 measurements were taken with 10 measurements per second rate. Then average frictional pressure losses and standard deviation were calculated. Results are presented in Table 8 and Figure 30.

Table 8.

	40 mm Tube		80 mm Tube	
Voltage	Average Frictional Pressure Losses	Standard Deviation	Average Frictional Pressure Losses	Standard Deviation
V	mBar	mBar	mBar	mBar
7	2.53736	0.07299	0.06602	0.05362
8	3.79571	0.07331	0.19348	0.05042
9	4.67957	0.05497	0.30433	0.05518
10	5.56889	0.06798	0.34586	0.06121
11	6.36236	0.04745	0.48350	0.05579
12	7.05356	0.06426	0.58212	0.05720

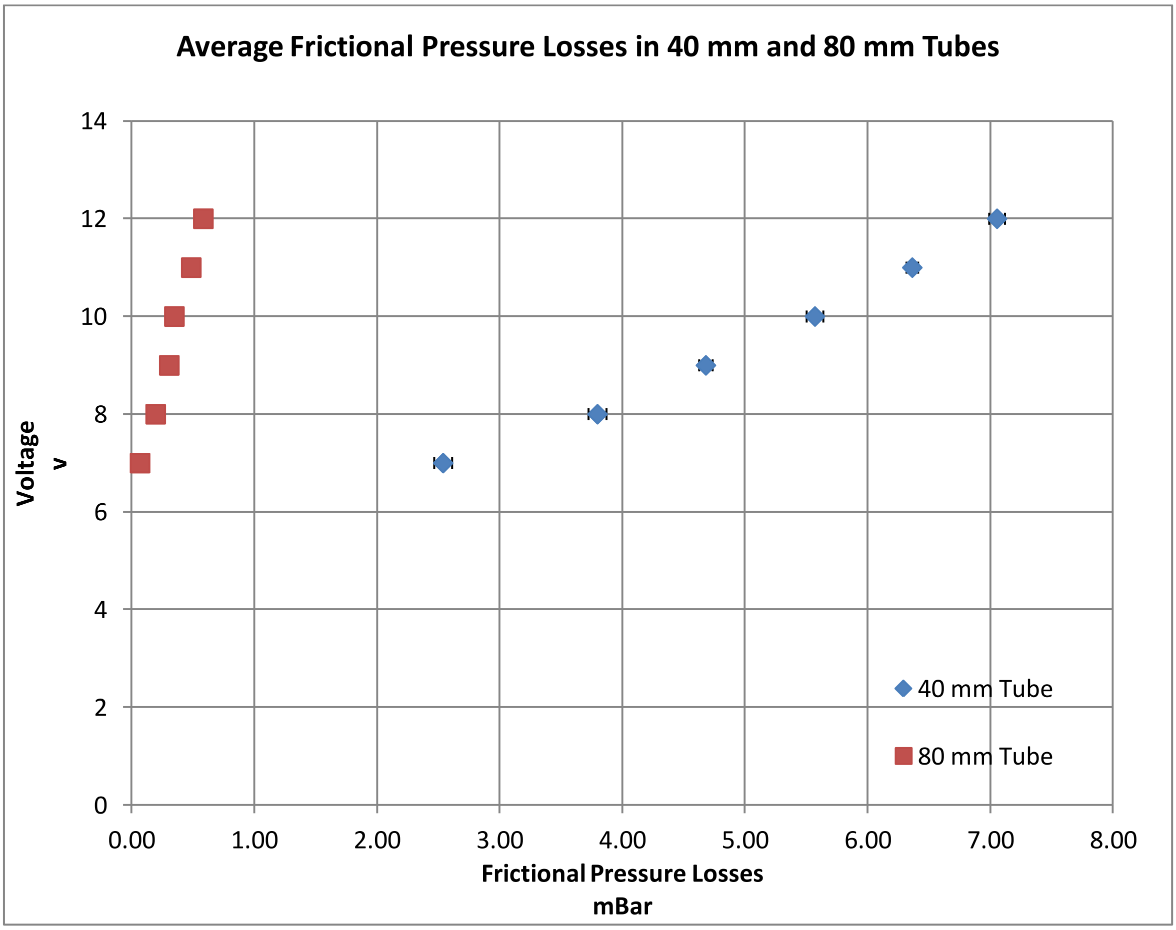

Figure 30. Average Frictional Pressure Losses in 40 mm and 80 mm Tubes.

The behavior of Taylor Bubble finds out to be similar to what was observed on 4 g/l PAC mixture. There was no single bubble tearing away from Taylor bubble. It should be noticed, that in high flow rates this low viscosity field channel obtains round-like form. The overall visual representation of Taylor Bubble behavior could be found in Appendix 1.

Figure 31.Fluid creates a channel in bubble in flow rates related to 12 v.

2.2.2.4. PAC mixture with concentration 2 g /l.

Pressure losses with no bubble

Pressure loss readings were conducted for flow rates equal to voltage from 6 to 12 volt with a step of 1 volt. For each voltage more than 5000 measurements were taken with 100 measurements per second rate. Then average frictional pressure losses and standard deviation were calculated. Results are presented in Table 9 and Figure 31.

Table 9.

	40 mm Tube		80 mm Tube	
Voltage	Average Frictional Pressure Losses	Standard Deviation	Average Frictional Pressure Losses	Standard Deviation
V	mBar	mBar	mBar	mBar
6	1.10273	0.07198	0.07027	0.03238
7	2.16998	0.04245	0.05145	0.03496
8	2.89027	0.06086	0.07864	0.06227
9	3.54849	0.05669	0.17963	0.04057
10	4.12848	0.04267	0.22908	0.07079
11	4.74413	0.07256	0.30572	0.05196
12	5.27149	0.05745	0.33135	0.04746

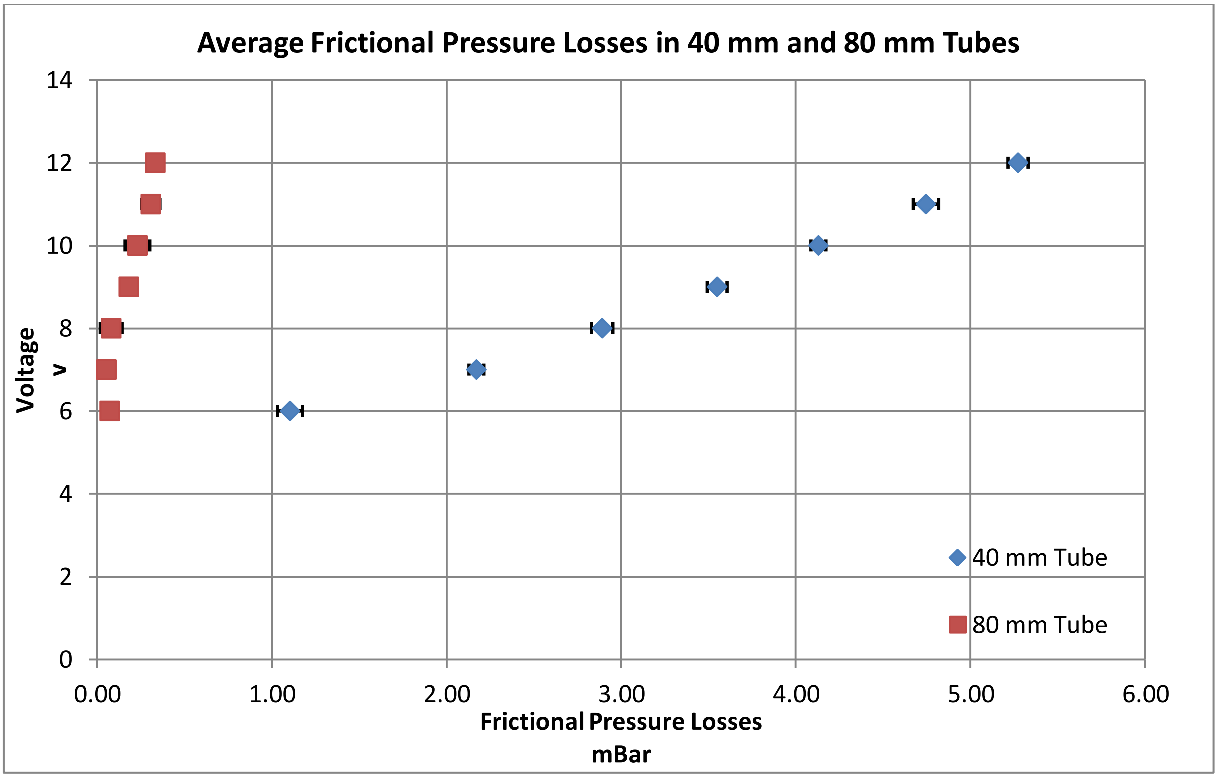

Figure 31.Average Frictional Pressure Losses in 40 mm and 80 mm Tubes.

Pressure losses with bubble

Taylor Bubble was introduced in flow rate equal to 7 volt. Then voltage was increased to 12 volt with a step of 1 volt. For each voltage more than 600 measurements were taken with 10 measurements per second rate. Then average frictional pressure losses and standard deviation were calculated. Results are presented in Table 10 and Figure 32.

Table 10.

	40 mm Tube		80 mm Tube	
Voltage	Average Frictional Pressure Losses	Standard Deviation	Average Frictional Pressure Losses	Standard Deviation
V	mBar	mBar	mBar	mBar
7	1.65655	0.07060	0.05084	0.03022
8	2.42009	0.05831	0.06817	0.05544
9	2.97642	0.06521	0.13501	0.07116
10	3.57911	0.04966	0.17485	0.04362
11	4.20924	0.07224	0.20471	0.05820
12	4.74554	0.07485	0.32410	0.04664

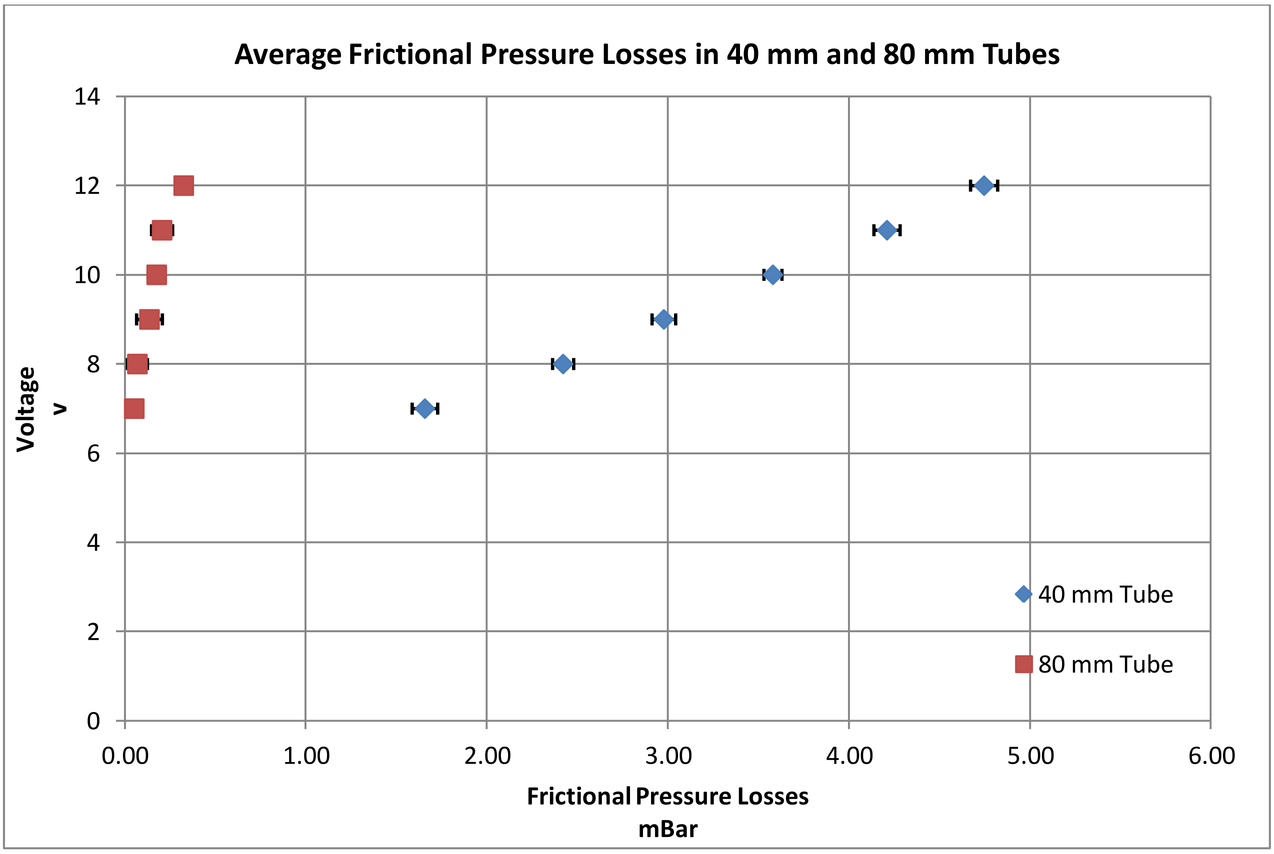

Figure 32.Average Frictional Pressure Losses in 40 mm and 80 mm Tubes.

Visual observation had shown slightly different behavior. Small amounts of bubbles start to tears from Taylor Bubble in flow rates equal to 11 volt. The tearing mechanism is different from water filled system. A big bubble tears away as a result of low viscosity field channel fluctuation, then this bubble get to the vortex where it breaks into smaller bubbles.

Figure 33. Bubble behavior at Flow rates relevant to 12 v.

After certain time this channel shifts towards center, creating higher velocity profile in a middle of the flow. It was also noticed, that small bubble in this system tends to move downwards faster comparing to water filled system. The overall visual representation of Taylor Bubble behavior could be found in Appendix 1.

2.2.2.5 PAC mixture with concentration 1 g /l.

Pressure losses with no bubble

Pressure loss readings were conducted for flow rates equal to voltage from 6 to 12 volt with a step of 1 volt. For each voltage more than 600 measurements were taken with 10 measurements per second rate. Then average frictional pressure losses and standard deviation were calculated. Results are presented in Table 11 and Figure 34.

Table 11.

	40 mm Tube		80 mm Tube	
Voltage	Average Frictional Pressure Losses	Standard Deviation	Average Frictional Pressure Losses	Standard Deviation
V	mBar	mBar	mBar	mBar
6	0.76746	0.04388	0.07726	0.03534
7	1.21941	0.06301	0.06127	0.03394
8	1.65256	0.07039	0.05103	0.02968
9	2.03944	0.05761	0.04959	0.03193
10	2.46168	0.05988	0.07146	0.05770
11	2.80380	0.08131	0.11033	0.07266
12	3.10943	0.07961	0.14139	0.07237

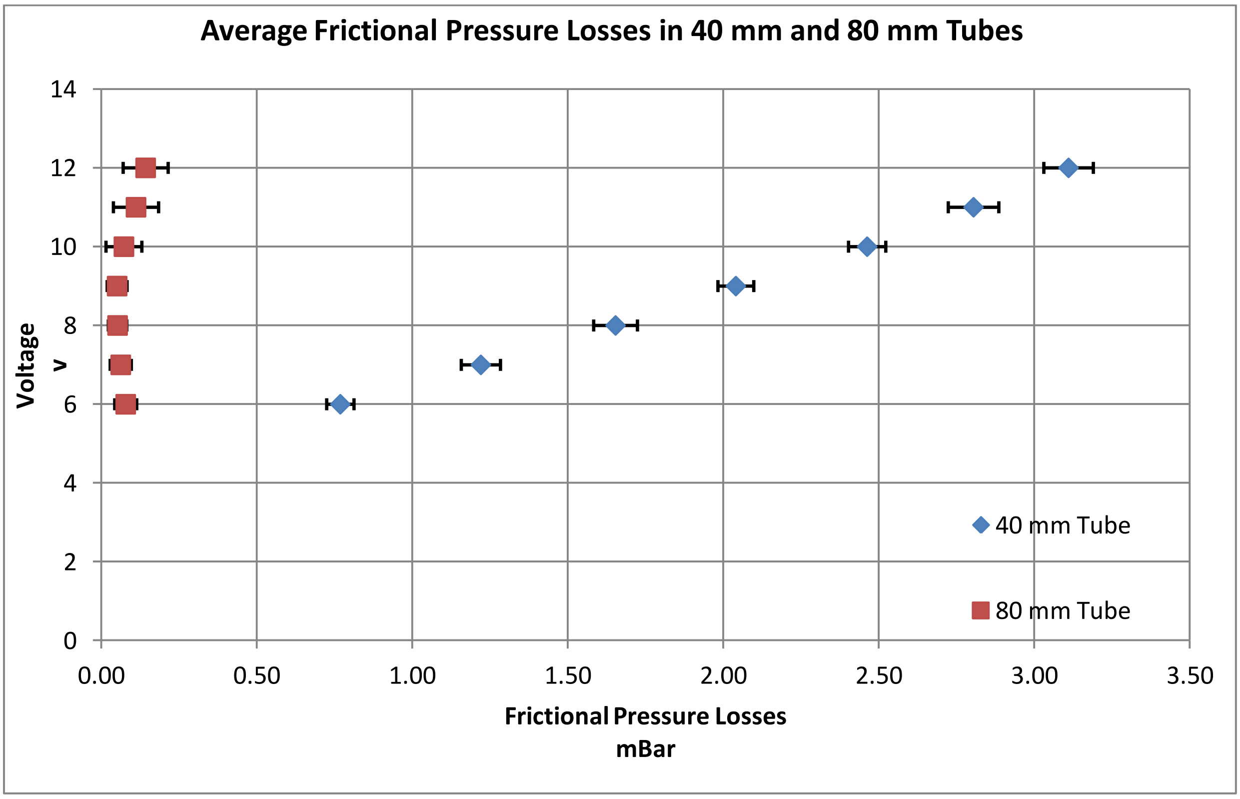

Figure 34. Average Frictional Pressure Losses in 40 mm and 80 mm Tubes.

Pressure losses with bubble

During conduction of preliminary experiment with bubbles it was noticed that fluid properties which defines the Taylor Bubble behavior and bubble tearing mechanism is closer to water filled system. So methodology of experiment was chosen to be similar to those for water. After obtaining a steady flow at 6v the bubble was introduced. Then, pressure readings were conducted for each voltage from 6v to 12 v and back with a step of 1 volt. However, the bubbles downward movement was found to be significantly faster comparing to water, so measuring time for each voltage was decreased to 1 minute. More than 600 measurements were made for each voltage with rate of 10 measurements per second.

Figure 35 represents experimental results. One should note that it takes approximately 30 seconds in order for voltage to be changed for 1 volt and for flow to be established (e.g. for fluid level in both 40 mm and 80 m tubes to be established). So those peaks in Figure 35 represents the time period of changing and establishing of the flow. The difference in bubble propagation could be found in Appendix 1.

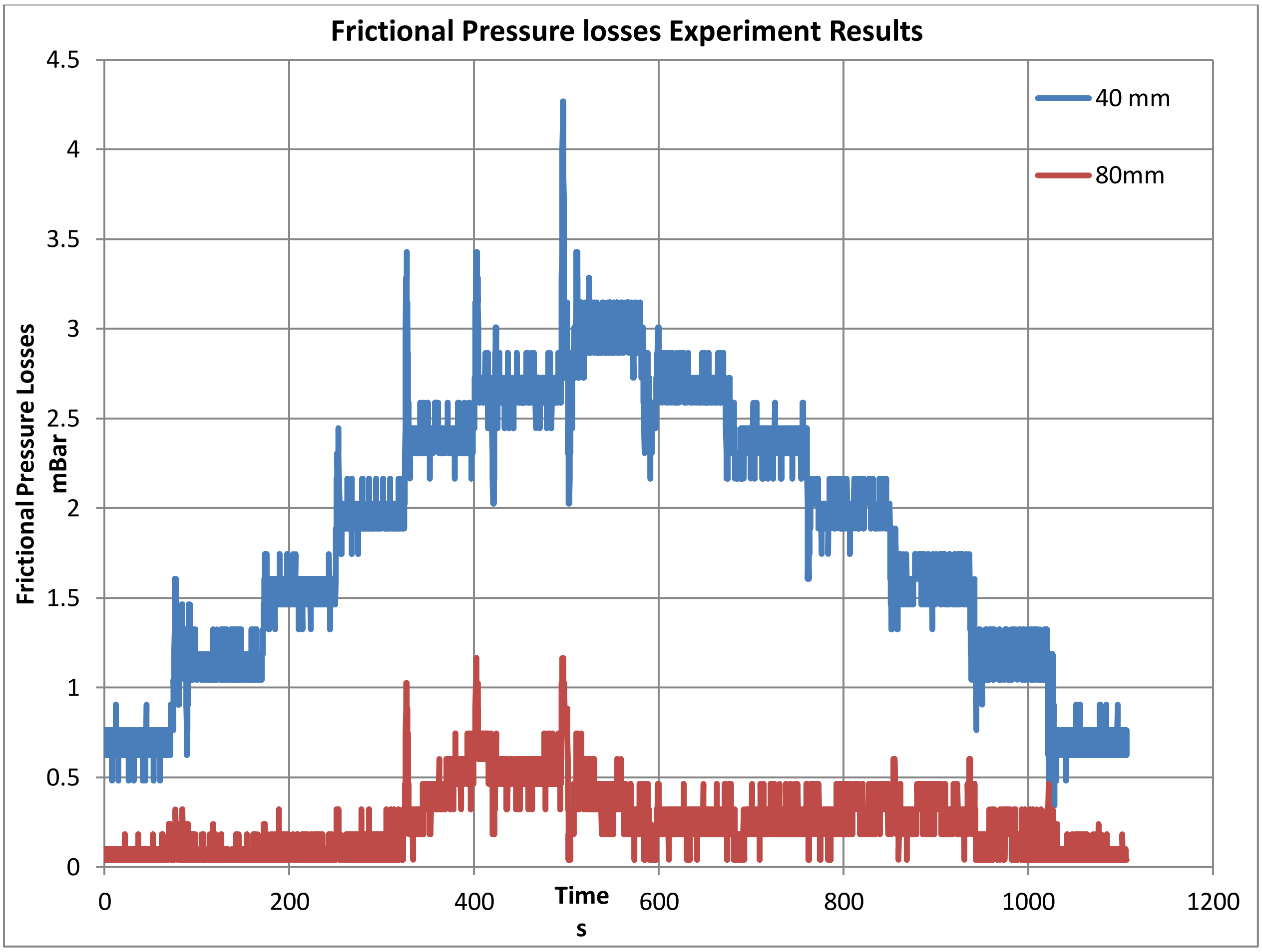

Figure 35. Frictional Pressure losses Experiment Results.

The average value and standard deviation was calculated for each voltage. Results are presented in Table 12 and Figure 36.

Table 12.

	40 mm Tube		80 mm Tube	
Voltage	Average Frictional Pressure Losses	Standard Deviation	Average Frictional Pressure Losses	Standard Deviation
V	mBar	mBar	mBar	mBar
6v	0.65849	0.06639	0.05958	0.02813
7v	1.17305	0.05090	0.04723	0.02369
8v	1.53322	0.10424	0.05838	0.04436
9v	1.99028	0.09937	0.13020	0.07245
10v	2.43461	0.17090	0.40817	0.16080
11v	2.64764	0.14346	0.52458	0.12044
12v	2.99296	0.29085	0.45920	0.21378
11v	2.70131	0.07348	0.26476	0.07299
10v	2.35625	0.08546	0.23959	0.09486
9v	2.01638	0.05679	0.31418	0.06574
8v	1.59845	0.04829	0.30951	0.06403
7v	1.18097	0.04738	0.16309	0.05869
6v	0.71422	0.13035	0.06902	0.06225

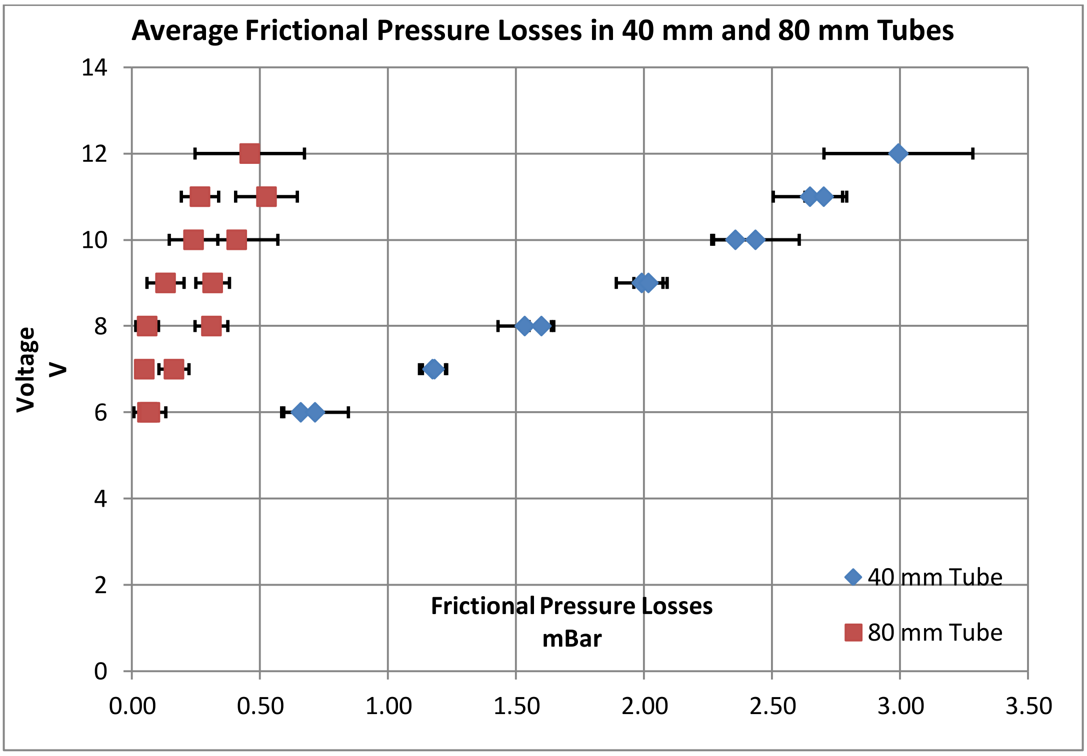

Figure 36. Average Frictional Pressure Losses in 40 mm and 80 mm Tubes.

TB breaks at flow rates equal to voltage of 10 volt and gather back in 9v. It should be noticed here, that smaller bubble tend to move downwards significantly faster compared to water filled system. Moreover, the energy of downward flow sufficient enough for bubbles to breakthrough in 40 mm tube. It can be noticed from pictures of bubble for 6v forward and back, that bubble volume decreased because of bubble breakthrough.

2.2.2.6. Rheology

Density

Density measurements results for PAC mixtures with different polymer concentration are presented at Table 13.

Table 13.

Polymer Concentration	Density	
	s.g	g /cm^3
4 g per l	1.0017	0.99988
3 g per l	1.0014	0.9996
2 g per l	1.0011	0.99926
1 g per l	1.0007	0.9989

Surface tension

Surface tension measurements results with temperature correlation and F factors are presented in Table 14 for PAC mixtures with different polymer concentration.

Table 14.

	SURFACE TENSION, mN/m			
	4 g per l	3 g per l	2 g per l	1 g per l
Measurement 1	70.2000	70.5000	70.2000	69.0000
Measurement 2	71.1000	70.5000	71.1000	68.5000
Measurement 3	70.8000	70.6000	70.7000	69.0000
Average	70.7000	70.5333	70.6667	68.8333
Temperature correlation factor	1.0320	1.0320	1.0320	1.0320
F factor	0.9933	0.9933	0.9933	0.9933
Final Value	72.4736	72.3027	72.4394	70.5601

Viscosity

Viscosity measurements results for PAC mixtures with different polymer concentration are presented at Figure 37.

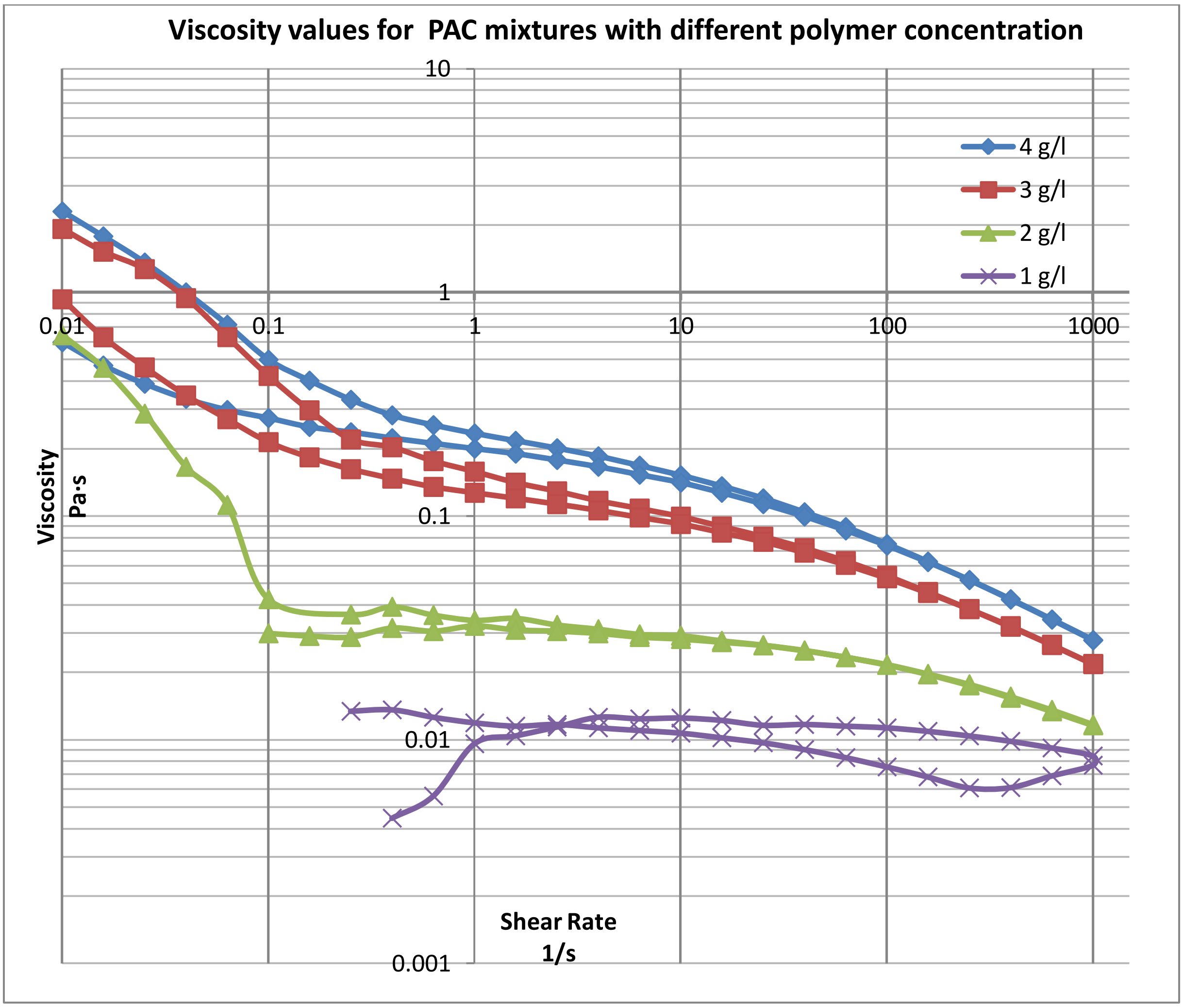

Figure 37. Viscosity values for PAC mixtures with different polymer concentration.

The hysteresis exists in all measurements results. The accuracy of 4 g/l and 3g/l is higher due to higher polymer concentration. Micro bubbles persistence is also possible in 2 g/l and 1g/l due to active bubble formation during experiment. It could be noticed, that for all concentration, except 1g/l, the hysteresis tends to zero value for shear rate higher than 10 s^{-1}. Viscosity measurements for all PAC mixtures confirmed shear thinning behavior.

Discussion

A behavior of Tailor Bubble in different counter current fluids was researched during conducted experiments. Significant difference was observed for water and for PAC mixtures with different polymer concentration. It was noticed how strongly rheology effects on bubble stability.

Although some improvements could be done, such as, but not limited to providing all rheological measurements before and after the experiment in order to improve accuracy. Another improvement would be to conduct pump calibration for PAC mixtures with polimer concentration 3 g/l, 2 g/l and 1 g/l.

3.Conclusion

In this Master Project a huge variety of Managed Pressure Drilling techniques was investigated from different points of view, advantages and disadvantages this drilling technique were defined and listed.

Although MPD implementation increase drilling costs and required high level of personnel competency, it can solve some of drilling problems like drilling in narrow pressure window and in highly fractured carbonate structures.

In experimental part of the project existing experimental facility was modified in order investigate Taylor Bubble behavior in counter current downwards fluid flow in vertical pipes. Ventury insert was installed to create a region of increased fluid velocity. Five different fluids were tested: water and PAC mixtures with polymer concentration 4,3,2 and 1 g/l. A 120 FPS video was taken to capture bubble behavior. Finally, pressure readings were conducted in order to define frictional pressure losses for different regions of facility.

Bubble behavior in different fluids was different. In systems filled with water and 1 g/l PAC mixture Taylor Bubble wake became distinctive at moderate flow rates, smaller bubbles tend to tear apart and move downwards. For 4 and 3 g/l PAC mixtures smaller bubbles does not tear from Taylor Bubble, and for 2 g/l PAC mixture bubbles tear only in high flow rates.

In terms of high flow rate pumping in order to force influx back, experiments with 1 g/l PAC mixture had shown best results. Taylor Bubble structure tends to breaks on smaller bubbles which are moved downwards by fluid flowing. This whole process is significantly faster comparing to water system.

In the end of the work done was reviewed and weak points were defined in order to provide a motivation for future research.

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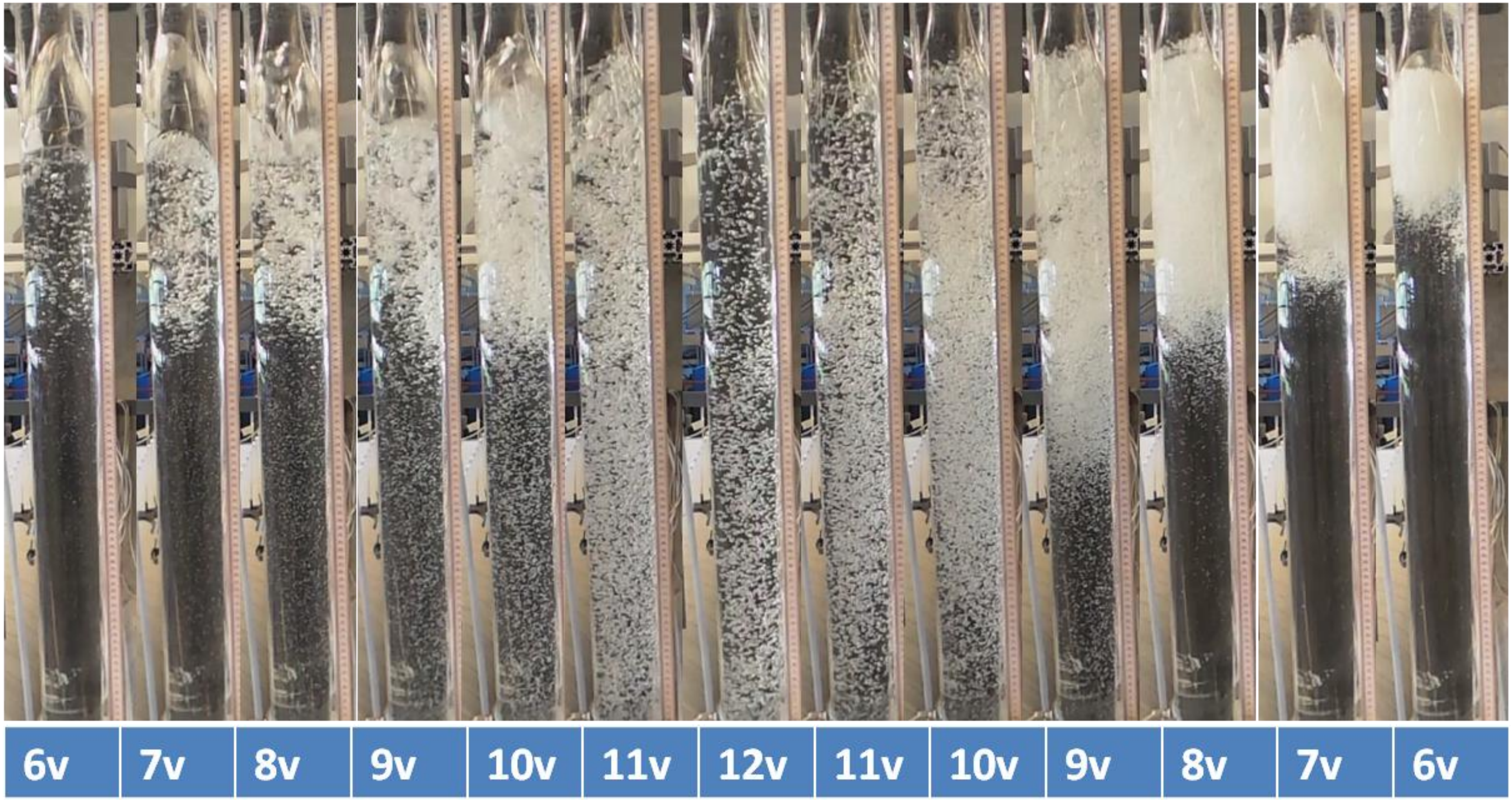
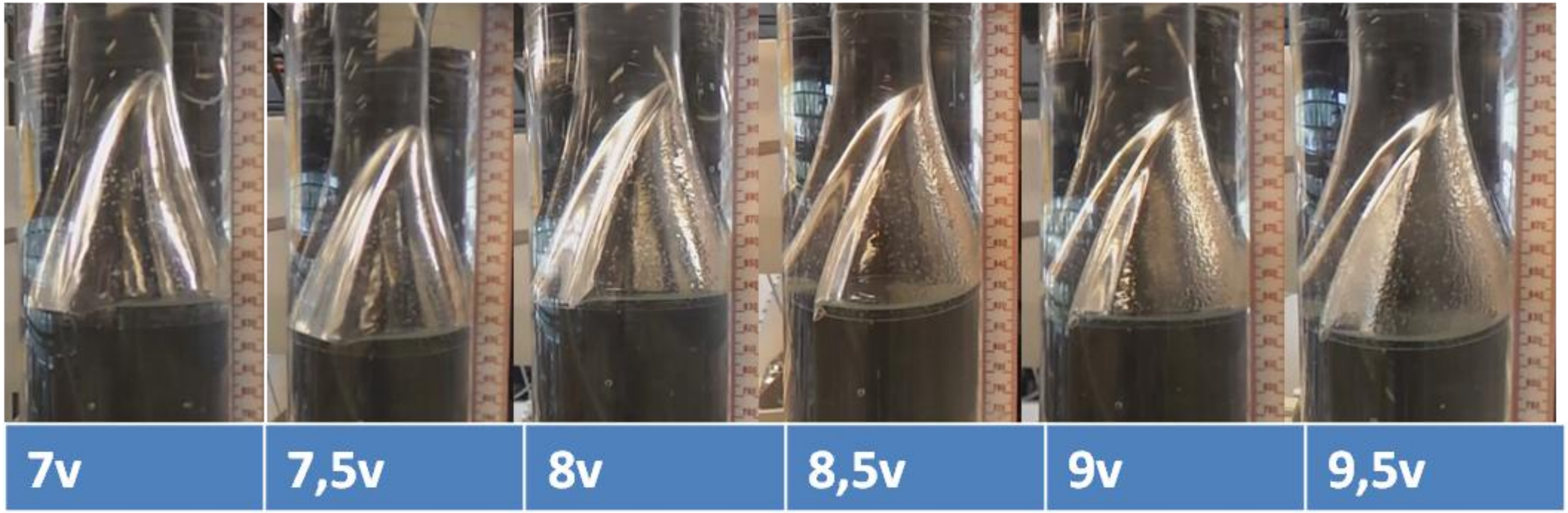
APPENDIX.

Water:



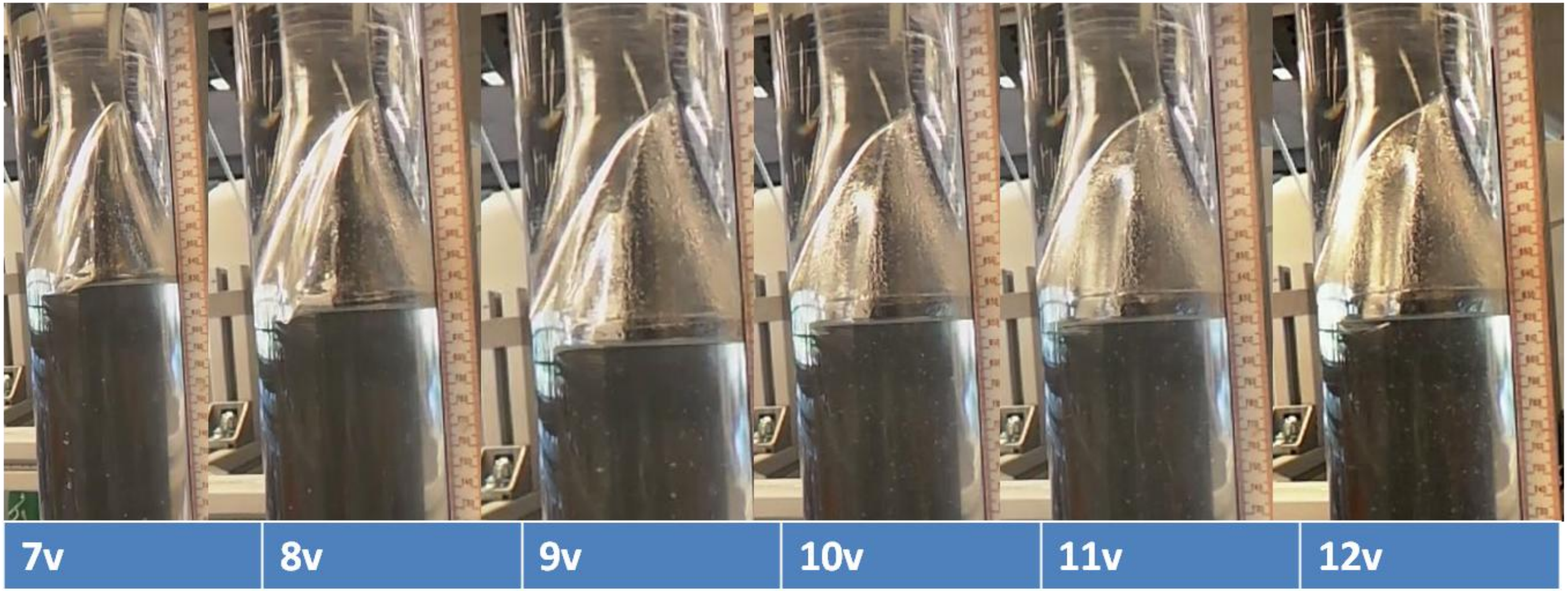
APPENDIX.

4 g/l PAC mixture:



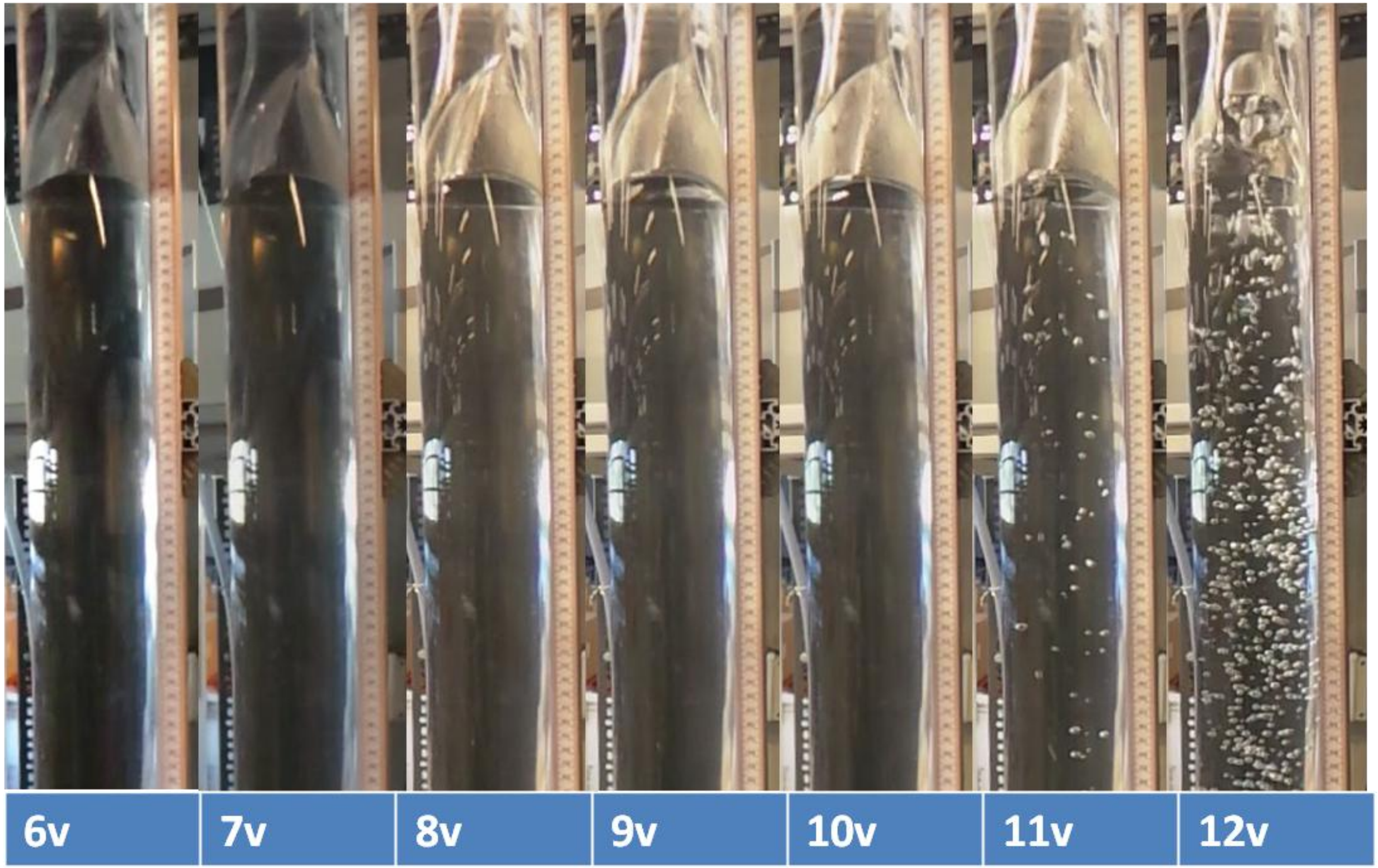
APPENDIX.

3 g/l PAC mixture:



APPENDIX.

2 g/l PAC mixture:



APPENDIX.

1 g/l PAC mixture: