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MASTER'S THESIS

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ABSTRACT

Primary and secondary oil depletion only recovers 20 – 50 % original oil in place (OOIP), so large amount of oil is still trapped in the reservoir after conventional processes. To recover more oil, tertiary methods are used to increase the amount of oil that can be extracted from an oil field. Enhanced oil recovery (EOR) is a tertiary method used to maximize oil recovery from the reservoirs. There are many different EOR methods, however, polymer injection and polymer flooding is the most important chemical EOR method used in sandstone reservoirs. It has been found that polymer flooding can recover from 2 – 5% OOIP over traditional water flooding.

Polymers are long chain molecules, often, with high molecular weight. These molecules increase the viscosity of the injection water and improve the mobility ratio, which is the mobility of the displacing phase divided by the mobility of the displaced phase. A mobility ratio of 1 between water and oil will increase the sweep efficiency. However, one of the main problems with polymer flooding is that polymers are very shear sensitive. During polymer injection, shear is especially to be found in process equipment, like fluid flow devices (valves, pumps), but also in the reservoir. When polymers are subjected to shear, they are readily broken down and degraded, which results in irreversible loss of viscosity and inefficient oil recovery. There are however low shear technologies and equipment which purpose is to reduce mechanical degradation of polymers during injection. Some of the state of the art low shear techniques rely on pipes and coils, while other relies on cyclonic principles. It is thought, that a reduction in pressure drop over a longer length (spiral) or in a bigger volume (cyclonic) will reduce shear forces, hence mechanical degradation of polymers.

This thesis consists of and is part of two industry projects, a pre-project and a main project between Typhonix, Total and the International Research institute of Stavanger (IRIS) and the Research Council of Norway. The aim of the pre-project and the ongoing main project is to study mechanical degradation of polymers by low shear valves and fluid flow devices, especially low shear Typhoon technologies. Typhonix AS, which is a company with knowledge within low shear process equipment, have patented a cyclonic low shear valve, the Typhoon Valve, and a low shear spiral fluid flow control device, the Shark. Both devices have proven to have a positive effect on oil in water emulsions, due to less shear forces and turbulence. In the Typhoon Valve, the pressure drop is reduced in a bigger volume than in a conventional valve, while in the Shark, the pressure drop is reduced over a longer length, resulting in less shear forces and turbulence. From previous study, it is to believe that a new low shear process for EOR polymer flooding can increase the recovery rate from 3 to 7 % .

The Typhoon Valve was tested at Total's division for polymer injection in Lacq, France (PERL). The Shark was tested at Typhonix's own laboratory at Varhaug, together with a small scale Typhoon Valve and a standard valve. In both test programs, a high concentration polymer solution was pumped through a test-rig where the Typhoon Valve (France) or the

Shark, small scale Typhoon Valve or standard valve were installed (Varhaug), at different flow rates and pressure drops. Different configurations of the Shark were tested, to see if different lengths and diameters had influence on polymer degradation. Samples were taken downstream the test-section, and the viscosity of the samples was measured with a rheometer. % degradation was then calculated, and the Typhoon Valve, the Shark, and the Typhoon configuration were compared to the results with the Standard valve.

The testing in France with the 2" Typhoon Valve did not give the positive results that were expected. It was observed that the degradation with the Typhoon Valve was in the same range as with the Standard Valve. It was also seen that the degradation was a function of both pressure drop and flow rate, as they increased, the degradation also increased. Especially with high pressure drop was % degradation in both valves was high (> 60%). It was found that the internals in the Typhoon Valve was not optimized for the test conditions, so this may be the reason for the disappointing results.

However, the testing at Varhaug with the different Shark configurations, gave very promising results. It was not observed any degradation of the solution, with any of the different cones and spirals, even at the highest pressure drop, and % degradation remained low. It was seen that the shear rates in the cones and spiral were less than the critical shear rate of the polymer. The viscosity did differ a little at very low shear rates when viscosity measurements were conducted, but this can be explained by high uncertainties and sound at low shear rates. Also, with the Typhoon configuration, the results were promising. It was observed that the valve gave less degradation of the polymer solution compared to a standard valve, especially at high pressure drops, and % degradation was lower than with the standard valve.

The experiments conduced, both in France and at Varhaug, gave knowledge about shear rates and shear degradation of polymer solutions in mechanical facilities. From the results further suggestions and further tests are planed to be conducted, for both the Typhoon Valve and the Shark.

 The Typhoon Valve are planed to be tested with new internals, such that optimized capacity is achieved. This testing is going to take place at Total's facilties in Lacq in autumn 2013.

Further tests with the Shark are also suggested. Tests with smaller diameter coils, and higher flow rates, to initiate shear should be conducted. The results should be compared to the shear degradation with a Standard valve. The shark can be constructed to have shear rates which is under the critical shear rate of the polymer, which means that polymer degradation is avoided. This is of outermost importance, to increase oil recovery, and reduce the amount of added polymer.

CONTENT

FIGURES

TABLES

1 *INTRODUCTION*

Mechanical degradation of polymer during polymer injection and polymer flooding, due to process equipment is the main topic in this thesis. Conventional valves may cause severe degradation of polymer solutions, and it is to believe that low shear valves and technologies can reduce mechanical degradation of polymer solutions.

This thesis consists of two main parts, a theory part with emphasis on polymer flooding and valve technologies, especially low shear valves, and a second experimental part, which describes testing of low shear valves and technologies, as well as the results. The low shear valve and technology is more specifically the Typhoon Valve and Typhonix's own flow control device, also named Shark. The methodologies and the results are divided into two main parts, the first part is the testing of the Typhoon Valve at Total's facilities in France, while the other part is the testing of the Shark at Typhonix's own laboratory.

1.1 *Background*

Enhanced oil recovery (EOR) is a tertiary method used to increase the amount of oil that can be extracted from an oil field. Polymer flooding is a well known chemical enhanced recovery method used to maximize the oil recovery from the reservoirs. The primary depletion and secondary water flooding of oil reservoirs typically recover only 20-50% of original oil in place, and hence the majority of oil still remains trapped after the application of these conventional processes [1]. Polymer flooding needs to be considered a mature technology and still the most important EOR chemical method in sandstone reservoirs based on the review of full-field case histories. Polymer addition increases the viscosity of the water which reduces fingering of the water, hence sweeps out more oil from the reservoir.

1.1.1 *Polymer*

Polymers are long chain molecules which increase the viscosity of the injection water, which then becomes a non-Newtonian fluid. By adding polymer to the injection water, the mobility ratio and vertical and areal sweep efficiency is improved, that means, more oil is swept out of the reservoir. However, the main problem with polymer flooding is mechanical degradation. Polymers are very susceptible to shear forces which are created in mechanical facilities, especially in fluid flow devices, like valves. Polymers are flexible chain molecules which can readily be broken down when they are submitted to shear, and this causes an irreversible loss of the solutions viscosity.

1.1.2 *Mechanical degradation in valves*

Degradation of polymers during polymer injection and flooding is especially high in fluid flow control devices, like valves and pumps, due to shear forces. There are however patented low shear valves and techniques which purpose are to reduce the mechanical degradation of polymers during injection. Some of the state of art techniques relies on pipes and coils, while

other techniques rely on cyclonic principles for minimize shear forces. The Typhoon Valve and the fluid flow control device, also called Shark, patented by Typhonix, and the low shear valve patented by Total is thought to reduce polymer degradation due to less shear and smoother fluid flow in the devices. The Typhoon valve relies on cyclonic principles, while the Shark and Total's valve rely on fluid flow in pipes, for a reduction in shear forces.

The Typhoon Valve, the flow control device and TOTAL's valve has been proven to be low – shear valves, and they may have a potential for reducing the degradation of polymer in polymer flooding, hence the viscosity of the injection water will increase. This is of outermost importance in enhanced oil recovery since increased viscosity of the injection water will sweep out more oil from the reservoir. A new low shear process for EOR polymer flooding has a potential for increasing the oil recovery rate with 3 to 7%, and would represent a "quantum leap" within EOR/IOR [30].

1.1.3   *Project history and the Typhoon Valve*

The Typhoon Valve is a low shear cyclonic valve which has been proved to reduce droplet break-up, as well as enhancing downstream separation [2].

The development of the Typhoon Valve has consisted of three subsequent projects

1) The Typhoon Valve Feasibility study (concluded 2006)
2) The Typhoon Valve development Project (concluded 2009)
3) The Pilot Installation and Testing of Typhoon Valve (ongoing)

The first concept study was done at the University of Stavanger in 2004/2005 as part of a PhD study. Since then the Typhoon Valve has been tested in both small and large scale flow rigs, and the separation benefits have been tested with different crudes and at different parameters. The Typhoon Development Project was financed by ConocoPhillips, Statoil, Shell, Eni, Total, Mokveld and the Research council (Petromaks). In the project it was concluded that the Typhoon Valve has a positive effect on the oil/water separation, in that both the oil and water quality was improved. The median oil droplets downstream the Typhoon Valve were also twice the size compared to droplets of the standard valve.

The concept behind the Typhoon Valve is cyclonic flow to control fluid pressure and flow rate. The internals in the Typhoon Valve includes:

1) A cage with tangentially oriented orifices which regulates and transform an axial inlet flow into a vortex flow
2) A venturi – shaped cyclonic body optimized to develop a suitable vortex pressure drop
3) A vortex breaker which transform the vortex flow back to an axial outlet flow

The result is less shear forces and turbulence compared to the flow in conventional valves. The petroleum fluid phases are thus mixed less together, and separate more readily in

downstream two or three phase separators. An illustration of the Typhoon Valve is given in figure 1-1 below.

Figure 1-1: The Typhoon Valve

The less shear forces and turbulence provided by the Typhoon Valve may be taken advantage of in polymer flooding, thus creating less degradation of the polymer and higher recovery of OOIP.

1.1.4   Typhonix's flow control device (Shark)

This flow control device, patented by Typhonix is a spiral shaped throttle valve, or control device for fluid flow control. The length, shape and cross sectional flow area of the spiral, and the number of spirals can be adjusted to achieve the desired turbulence and pressure drop for a given fluid flow. This means, that unwanted effects like fluid mixing, particle erosion, cavitation erosion and noise and valve vibration is reduced. Figure 1-2 below illustrates the Shark.
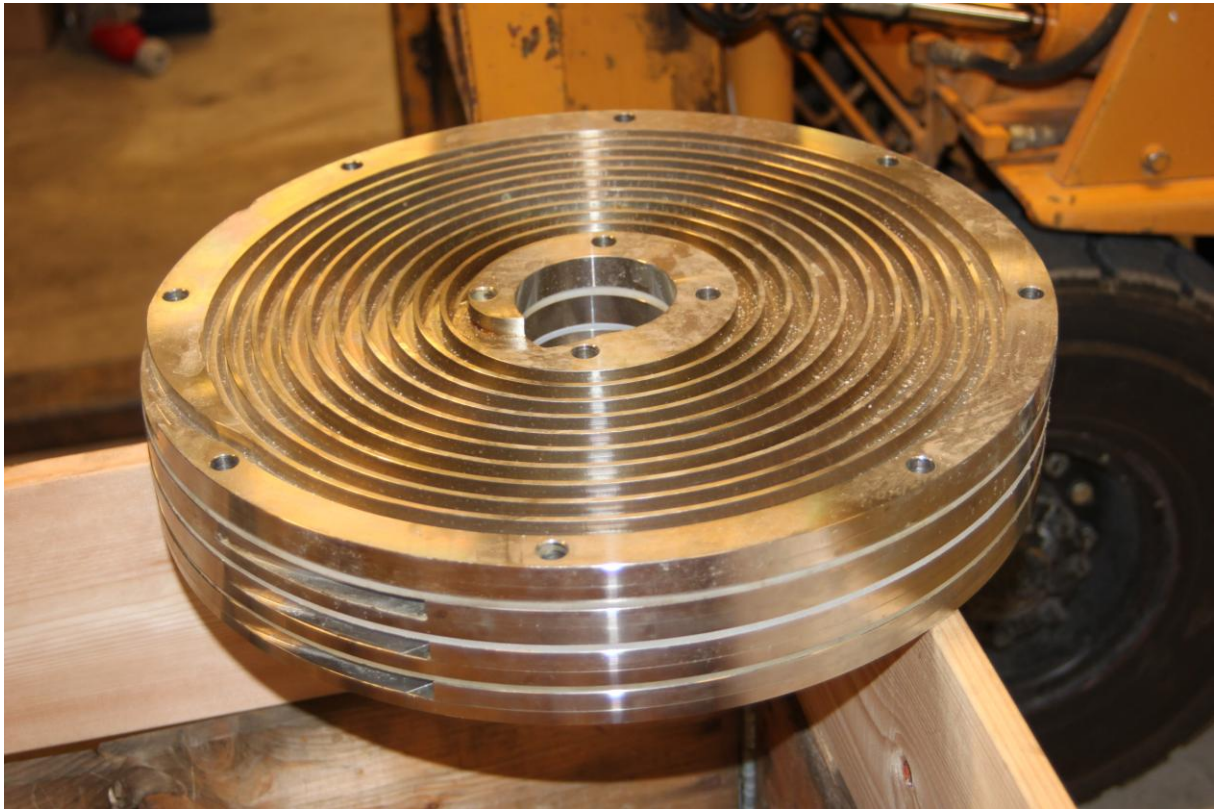
Figure 1-2: Illustration of the Shark

The main purpose of the present invention is to increase coalescence of oil droplets in water to increase the downstream separation of oil and water, and to reduce emulsification. But, it is thought, that because the pressure drop and turbulence can be adjusted, it can also be used as a flow control device in polymer injection. The turbulence, hence the shear rate can be set to a minimum by adding adjusting the length and the diameter of the spirals.

1.1.5   *Total's valve for polymer injection*
TOTAL has patented a flow control valve, made solely for polymer solutions. The invention consists of both a method for transportation of the solution, as well as a method for injecting the solution into a subterranean formation, using a flow control valve, with minimized mechanical degradation. The device consists of a single injection pipe, and a flow control valve which contains at least 10 fluid transport tubes arranged in parallel. The tubes should have identical shapes, but it is preferred that the sections are not all identical. By having some tubes with relatively large section, and some tubes with small sections, the pressure drop can be adjusted. Fluid flow through the tubes with large sections results in reduced pressure drop, while fluid flow in the tubes with small sections results in increased pressure drop.   The geometric characteristics of the flow control valve, namely the size, number and length of the fluid transport pipes are selected as a function of the flow rate range and the pressure drop range which is desired, such that minimal degradation of polymer occurs.

2 *POLYMER INJECTION*

2.1 *Earlier findings*

In the early 1900's the problem of inefficient oil recovery was recognized. Polymers are long chain molecules combined of monomers. They are added to the reservoir to increase the viscosity of the injection water, which will then sweep out more oil from the reservoir. Reservoir oil is normally ten times more viscous than the water flood, but addition of polymer viscosify the water, causes it to push out more oil than conventional (primary and secondary) methods do. The sweeping of oil is called the "piston" effect and may enhance the oil recovery by 5% - 15% [3]. The enhanced oil recovery depends on mobility, and polymer injection improves the mobility ratio [4]. Mobility is how permeable a porous media is to a given phase, divided by the viscosity of the phase. Mobility ratio is the mobility of the displacing phase divided by the mobility of the displaced face. In polymer flooding, polymer containing water is the displacing phase, and oil is the displaced phase, as equation 2.1 below illustrates [5].

$$M = \frac{\lambda w}{\lambda o} = \frac{\mu w / K w}{\mu o / K o} \qquad\qquad (2.1)$$

- λ = Mobility
- μ = Viscosity
- K = Effective permeability

A mobility ratio of 1 between water and the oil will increase the sweep effect. The addition of polymer will increase μw hence decrease M. Polymer flooding improves areal sweep, vertical conformance and reduced water production. Addition of a small amount of polymer (0.1% − 1%) may increase the viscosity of the injection water by 10 to 100 fold [6]. The injection water then becomes a non-Newtonian fluid, which means that the water does not have a constant viscosity. Polymer flooding has highest impact in reservoir with high permeability and high oil/water viscosity ratio (10 − 100), since the polymer injection improves the mobility ratio. The most used polymer for polymer flooding is hydrolyzed polyacrylamide (HPAM).

The first attempts to improve sweep efficiency by polymer flooding were made by Detling in 1944, and polymer flooding became a method to enhance the oil recovery in 1964 after Pye and Sandiford found that the mobility of water used in water flooding could be reduced by adding small amounts of water soluble polymer [7, 8]. The reduction in water mobility resulted in greater oil recovery [9]. Extensive research has been abducted since then to improve sweep efficiency in oil recovery from the reservoirs by polymer flooding. During the 1980's a commercial polymer flood was developed in North Burbank which demonstrated that this EOR method had a potential to increase oil recovery in mature basins. From statistical data, the incremental recovery from polymer flooding was on average 2 − 5% OOIP

over water flooding in the 1980's, when using low molecular weight polymers and small polymer – bank sizes [10].

Typically, polymer flooding involves injection and mixing of polymer over an extended period of time, until 1/3 – ½ of the reservoir pore volume has been injected [11]. Then a continued long term water flooding follows. The water flooding drives the polymer slug and the oil bank towards the production wells.

Significant laboratory studies and field test results have confirmed that polymer will improve the mobility ratio, and hence sweep out more oil. But recent studies have also shown other properties of polymer, and one of these properties is that polymers are very unstable. Studies have shown that polymers are very sensitive to mechanical, chemical, thermal and microbial degradations. Polyacrylamide is especially sensitive to salt content, mechanical shear stress, high temperature and content of H_2S and bacteria. The structure of the polymer may also be damaged during production, injection and operation, which causes an irreversible loss of viscosity. The susceptibility to mechanical or shear induced degradation of HPAM decide if the polymer can be used, but most of the polyacrylamides have very high susceptibility to mechanical shear stress. HPAM is especially susceptible degradation at high fluxes and flow through valves, orifices and at low permeability formations [12]. Shear degradation breaks the macromolecular chain which induces strong reduction in macromolecular size and viscosity. High molecular weight hydrolyzed polyacrylamide are more sensitive to shear degradation than low molecular weight polymers. Low molecular weight polymers may be a better choice for field applications when shearing conditions are not well controlled, especially with flow through down hole valves [13].

When polymers are submitted to high shear, they may readily be broken down. The potential shear locations are

1. The polymer dissolution facilities: static mixers and pumps
2. The injection lines: particularly the well head chokes
3. The well bore entry

The analysis of the shearing conditions done by TOTAL (Morel 2008 and 2010) [14, 15] showed that the highest shearing device is the well head choke. Due to shearing conditions in this choke, up to 25 – 50% loss in viscosity has been observed.

Other possible stages where mechanical shearing of the polymer may occur are during handling and injection processes [14]

1. During polymer dissolution in makeup water in shearing devices
2. In centrifugal pumps during recirculation

And flow through [13]:

3. Chokes under differential pressure
4. Downhole valves

5. Perforations and sandface

Usually, a viscosity loss of 10 – 20% is acceptable, but a higher loss in viscosity may compromise the project.

The degradation is also dependent on the retention time in the shearing device. The susceptibility to mechanical degradation offers practical problems in the field operation. Maerker [16, 17] has presented a comprehensive study on shear degradation with polymer solutions with a concentration of 300 ppm to 600 ppm at different conditions. The studies showed that degradations has a moderate effect on viscosity ($< 5\%$ loss), but high impact on screen factors ($>90\%$ loss). Shear degradation became severe especially at high fluxes, at low permeability formations and at high salinities.

Earlier field tests have also shown that due to mechanical shear at the injection point and in the mixing facilities, the actual concentration of polymer in the reservoir after injection is much lower than the original injected solution [12]. Both in the Taber South field and in the West Semlek field were the polymer concentration lower in the injection water than it was before injection.

It is only when the polymer is dissolved that the shear forces are harmful and degradation of the polymer occur [18]. When the polymer is dissolved, the high shear in valves may cause degradation, dependent on pressure drop and the nature of the brine used. Many wells are operating to receive full flow without valves because of this mechanical degradation. Small diameter down hole tubing has been used when it is necessarily to restrict flow control.

Until now, the well known problem with polymer degradation has been solved by adding more polymer and use higher concentrations. This is expensive, and may have a negative impact on the environment, and a more complex separation process for the produced well stream is needed.

The answer of the degradation problem may be solved with new technologies, especially low shear technologies. Typhonix, which have become an expert in low shear technologies have developed both a low shear Typhoon Valve, and a flow control device. It is documented through laboratory and full scale experiments that Typhoon valve is a separation friendly and a low-shear valve. The low-shear valve may reduce the degradation of polymers. Turbulence is the sole mechanism for polymer degradation, and with the Typhoon valve the turbulence will be minimized, hence gives less degradation. The low shear control device has also been proven to have a positive effect on oil droplets break-up and coalescence.

2.2   Types of polymer

In polymer flooding there are two types of polymers that are frequently used:

1) A synthetic polymer (hydrolyzed polyacrylamide)
2) Biologically produced polymer (Xanthan gum)

Hydrolyzed polyacrylamide (HPAM) is synthesized from their monomers in a chemical reactor. Polymers are long chain molecules combined of monomers. They are added to the reservoir to increase the viscosity of the injection water, which will then sweep out more oil from the reservoir. The performance of HPAM in polymer flooding is dependent on its molecular weight. Higher molecular weight polymer increases the viscosity and resistance factor to a greater extent than low molecular weight polymers. In HPAM, some of the acrylamide is converted into acrylic acid which increases the viscosity and stability in fresh water, but reduces the viscosity in hard water (water with high concentration of divalent and trivalent ions) [9]. The increased stability is a result of increased rigidity, which is provided by charge repulsions [13]. In addition to increase the viscosity, HPAM also alters the permeability of the reservoir rocks, which in turn lowers the mobility of the injected water. Reduced permeability of reservoir rocks means that a lower concentration of polymer is to be used to achieve equivalent mobility control than for high permeability reservoir rocks. One of HPAM's disadvantages is that it is very salt sensitive, therefore freshwater (total dissolved solids < 10000 ppm) has to be used when preparing these solutions. Salt cations in the water screen the negative charges on the acrylate groups in the polymer, which induce coil shrinking and drop in viscosity [13]. Polyacrylamide is also very sensitive to shear stress [9], especially those with high molecular weight are easily degraded by mechanically shear. Special care is therefore needed when handling this type of polymer.

Polyacrylamides are available in different forms. For a large scale application HPAM comes in powder form (90% + active), pumpable inverse emulsion (22 to 55% active) or it can be manufactured on site in a concentrated solution [4].

Xanthan's gum is the most used biopolymers, and is derived from fermentation processes. This biopolymer is produced by the bacterium *Xanthomonas campestris* [4]. When *Xanthomonas campestris* is cultured in a suitable fermentation medium, they produce Xanthan gum as a byproduct of their metabolic processes. The byproduct is then separated from the rest of the cell material and sold as a concentrated broth, and contains typically 3 – 13% active polymer. Their molecular weight is lower than for HPAM, but its structure gives the molecule great stiffness and relatively insensitive to salinity. This in turn gives them excellent viscosifying effect in high – salinity waters, and low susceptibility to shear degradation. This makes Xanthan gum easier to handle in field injection pumps and other equipment where shear degradation may occur. Their disadvantage is their low viscosifying power in fresh water. Biopolymers are not retained on rock surfaces, so they propagate more readily into a formation than HPAM. This may reduce the amount of polymers needed for a flood, but on the other side there is no or little residual resistance effect, hence the mobility will not decrease as much as it does for HPAM. To achieve the same resistance effect and reduced mobility, a higher concentration of Xanthan be used. Another disadvantage with Xanthan is their susceptibility of formation plugging and bacterial attack. Filtration of the solution, and addition of bactericides to prevent bacterial degradation can remedy these problems, but on the expense of higher costs.

Both HPAM and Xanthan gum are restricted in the range of reservoir conditions. Biopolymers normally degrades fast at temperatures > 250°F [93°C], and HPAM normally precipitate in waters containing high concentration of Ca^{2+} at temperatures above 160°F. This is normally not a problem in fresh water, but in high salinity water is compromise a huge problem [12, 18].

The different properties of both HPAM and Xanthan gum are summarized in table 2-1 below [12].

Type of degradation	Susceptibility		Cause	Remarks
	Polyacrylamide	Xanthan gum		
Chemical	High	Moderate	The cations Na^{2+}, Ca^{2+}, Mg^{2+}	Divalent ions are more detrimental
Chemical	High	High	Transition metal ions	Aggravated by high temperature and pH
Chemical	High	High	Oxygen or oxidizing agents	Aggravated by high temperature
Chemical	High	High	Hydrolysis by acid/basic chemicals	Aggravated under aerobic conditions or high temperature
Thermal	High > 250°F	High > 160°F	High temperature	Aggravated under aerobic conditions or high temperature
Microbial	Moderate	High	Yeast, bacteria, fungi	Aggravated under aerobic conditions or high temperature
Mechanical/shear	High	Low	Intense shear stress and high flux such as that occurring with flow through valves, orifices, and low permeability formations	

Table 2-1: Differences in properties between HPAM and Xanthan gum

2.3 Reservoir conditions favorable to polymer flooding

Polymer flooding depends on many factors. Among some of these factors are reservoir temperature, brine salinity, mobile oil saturation, water – oil mobility ratio, reservoir fluid properties and rock properties [12]. All of these factors should be screened to eliminate candidates with poor prospect, and identifying candidates with good potential with respect to polymer flooding.

2.3.1 Mobility ratio

The water – oil mobility ratio in the reservoir should range from $1 - 42$. Reservoirs with high (> 50) or low (< 1.0) mobility ratio should be avoided. Oil viscosity parameter can be used as a screening guide if the mobility ratio is not available. It is preferred to use oil with viscosity ranging from $5 - 125$ cp. Oil with viscosity ranging from $125 - 200$ may also be considered if the other parameters are favorable. The disadvantage with high viscosity oils is the excess polymer required to improve mobility control. This affects injectivity and the economics.

2.3.2 Reservoir temperature

Both polyacrylamide and Xanthan gum are sensitive to thermal degradation. At temperatures above 160 °F, polyacrylamide may precipitate, especially in saline water. At temperature above 250°F it will degrade. Xanthan gum will degrade at temperature above 160 °F. These limits are for reservoir which are oxygen, microbial, transition – metal ion and multivalent – cation free. Reservoirs with temperature above this range should therefore be eliminated.

2.3.3 Mobile oil saturation

Reservoirs with high mobile oil saturation (> 10% PV) are more suitable for polymer flooding, because polymer flooding will not improve displacement efficiency significantly.

2.3.4 Reservoir permeability

Low – permeation formations should be avoided. The reason why is because a polymer solution has lower mobility than water or brine. When injecting a polymer solution into a low permeability formation, two problems may arise:

1) The injection rate would be reduced, which means that the life of the project would be prolonged, this affects the economy
2) Degradation of polyacrylamides around injection wellbores due to high shear

Because of these problems, reservoirs with permeability below 20 md should be avoided.

2.3.5 Reservoir type

Sandstone formations are the most frequently used reservoir formations in polymer flooding. However, carbonate reservoirs have also showed encouraging results. Polymer flooding should therefore not be restricted to only sandstone formations. Special care should be taken when evaluating carbonate reservoir, due to their heterogeneity and high Ca^{2+} and Mg^{2+} content. Vugular and highly fractured reservoir should be avoided.

2.3.6 Reservoir porosity

Porosity can be divided into two groups:
1. Total porosity
2. Effective porosity, which again can be divided into
   - Intercrystalline - intergranular porosity
   - Fracture matrix porosity

Total porosity refers to the total void space, connected or not, while effective porosity refers to only the connected void space.

The recovery efficiency of polymer flooding depends on the type and nature of porosity. Porosity determines the oil in place, and the volume of recoverable oil present for a given oil saturation. The reservoir porosity also determines the total amount of polymer needed for a given polymer flooding. The pore surfaces and space also influences the flow, adsorption and

retention characteristics of the reservoir rocks. The presence and absence of clay in pore rocks have a great influence on flow behavior and the permeability of the reservoir rocks [9].

2.3.7 *Reservoir depth*

Because of pressure limits, both deep and shallow reservoirs should be avoided. In shallow reservoirs, injection pressure is a limitation. Pressure limit are especially important when combined with low permeability. Special infectivity tests are required for reservoirs less than 500 ft and less than 50 md in permeability before polymer flood can be applied. Within deep formations there is normally high temperature and high salinity, which makes these reservoirs unsuitable for polymer flooding.

Table 2-2 summarizes the screening criteria for reservoirs [12].

Screening criteria		*Values*
Reservoir temperature	Polyacrylamid	< 200 °F for degradation, < 160 °F for precipitation
	Xanthan gum	< 160 °F
Crude oil viscosity		< 200 cp
Water – oil mobility ratio		> 1
Mobile oil saturation		> 10 % PV
WOR		< 15
Average reservoir permeability		> 20 md
Lithology		Sandstone reservoirs is preferred, but calcium reservoirs can also be used

Table 2-2: screening criteria for reservoirs suitable for polymer flooding

2.4 *Shear degradation analysis*

An analytical technique to measure the degradation of the polymer during injection and flooding is by the use of a rheometer. This is a laboratory device used to measure how a fluid, slurry or emulsion is affected by applied forces. The device measures the rheology of the fluid. Rheology is a greek word for measuring the flow. There are many different rheometers, and they can be divided into two types. The first type is shear rheometers which control the applied shear stress. The other type is extensional rheometers which apply extensional stress. Rheometer proceduer is described in more detail in chapter 5 (methodologies).

In a rheometer there are several different templates which can be used to calculate the viscosity as a function of applied shear stress. A typical viscosity analysis curve, when plotting viscosity on the y-axis and shear rate on the x-axis is shown in figure 2-1 [19].
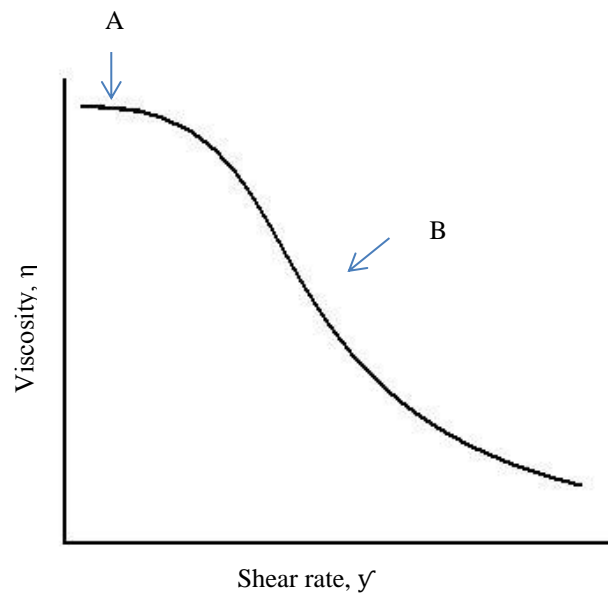
Figure 2-1: Standard curve after viscosity analysis of e shear thinning polymer

At low shear rate the viscosity is almost constant, this shear rate is called Newtonian shear rate (A). All polymers are Newtonian fluids at low shear rates, however, when the shear rates increases, the polymer starts to degrade. The point at which the polymer starts to degrade is called critical shear rate. When the shear rate increases, the viscosity is reduced, due to shear thinning effects (B). This is almost always true for polymers which are shear thinning.

2.5 Viscosity and rheology

Viscosity is a measure of a fluids resistance to flow, it is a fluids "thickness" or "internal friction". The less viscous a fluid is, the easier will it flow. All fluids have some resistance to stress, therefore all fluids are viscous, thus some are more viscous than others, and have more flow resistance. Water has low viscosity, it can easily flow without resistance, and in other words water is "thin". It is common to say that fluids which have less viscosity than water is a mobile fluid, while fluids with higher viscosity than water is a viscous fluid.

Viscosity is defined in equation 2.2 below [20]

$$\eta = \tau/\gamma \qquad\qquad (2.2)$$

Where:
η = viscosity
τ = shear tension
γ = shear rate

2.5.1 Types of viscosity

There are different types of viscosity [21]. Polymers are most often shear thinning, but can be Newtonian at low shear rates.

- Newtonian: Newtonian fluids are fluids with constant viscosity. Examples are water and gases.
- Shear thickening: Fluids which viscosity increases with shear stress.
- Shear thinning: Fluids which viscosity decreases with shear stress.
- Thixotropic: Materials or fluids which become less viscous over time when shaken agitated or stressed.
- Rheopectic: Materials or fluids which become more viscous over time when shaken agitated or stressed.
- A Bingham plastic: material that behaves as a solid at low stresses, but flows as a viscous fluid at high stresses.
- A Magnetorheological fluid: is a fluid which becomes more viscous when submitted to magnetic fields.

2.5.2 Viscosity coefficients

Viscosity can have different coefficients; depending on how is it measured [21].

- Dynamic viscosity (absolute viscosity): this is the most used coefficient, and is measured in Poise, P.
- Kinematic viscosity: this is dynamic viscosity divided by the density. Usually measured in Cm^2/s or in Stokes, St.
- Shear viscosity: this is the most important one, and is referred to as only viscosity. It describes the reaction to applied shear stress. In other words, it is the ratio between the pressures exerted on the surface of a fluid, in either vertical or horizontal direction to the change in velocity of the fluid when you move down the velocity gradient (move down in fluid).
- Volume viscosity: when fluid compressibility is essential, this coefficient is important. Is also called bulk viscosity.
- Extensional viscosity: This is a linear combination of both shear and bulk viscosity, and describes the reaction to elongation. Is especially important when characterizing polymers and their viscosity.

2.6 Field experience

There have been carried out many field experiences with polymer injection and polymer flooding. Two of them are described in the subchapters below.

2.6.1 Daqing (China)

The potential for polymer flooding began as a laboratory research in 1960. In 1972, a single – injector polymer flood with a small well spacing of 75 m was conducted, and polymer

flooding was then set on a pilot test [22]. In the late 1980's the pilot project in central Daqing was expanded, and a multi-well pattern with larger well spacing were used. From these tests, the results were positive, and together with extensive research and engineering through the 1990's, it was concluded that polymer flooding was the preferred method to improve areal and vertical sweep efficiency at Daqing. The world's largest polymer flood was then implemented at Daqing in 1996. The oil produced from polymer flooding contributed to 22.3% of the total production in 2007, and the ultimate recovery was boosted to more than 50% of OOIP. That was 10 – 12% more than with water flooding and an increase in the incremental OOIP in the 1980's. Table 2-3 below show some different parameters for the field.

Depth	1000 m
Temperature	45 °C
Oil viscosity	6 – 9 cp
Total salinity	3000 – 7000 mg/l

Table 2-3: Different parameters for the Daqing field

With only water flooding, the endpoint mobility ratio was 9.4. By injecting polymer, the mobility ratio was decreased, and when there were no or little polymer degradation, the ratio was decreased down to 0.3. The viscosity of the injected polymer solution was typically 35 – 40 cp.

2.6.2   Dalia Angola Case

2.6.2.1   Feasibility study
A feasibility study of polymer injection has been done in the Dalia field in Angola [14, 15]. This study started in 2003. The Dalia field is a deep – offshore, low temperature (50 degrees), high permeability (> 1D) sandstone reservoir which contains medium viscosity oil (3 – 7 cP). During this study, high molecular weight hydrolyzed polyacrylamide was found to be effective at a wide range of salinities.

For deep – offshore fields, powder polymer supply is achievable either with a specific bulk carrier or using standard international containers to transport big bags (750 kg). The polymer can be processed either on – deck, which is the simplest method, or on a barge connected to the FPSO.

The feasibility study was done to demonstrate the potential benefits of injecting polymer. A dedicated laboratory program was launched to select a polymer and the basic data needed to perform a sound evaluation of incremental oil brought by the polymer. Resource estimation was done by stimulation with and without polymer with specialized software and laboratory input parameters.

Based on literature survey, a concentration of 500 – 1500 ppm polymer is normal to use during polymer flooding. This corresponds to 30 – 90 ktons/year of polymer required. By the

two main types of polymer, hydrolyzed polyacrylamide has most advantages, with respect to the massive quantities of polymer needed.

A skid dedicated to the injectivity test has been made to prepare mother solutions. The skid was tested in France before it was shipped to Luanda for installation on the FPSO during summer 2008. And injectivity pilot was also done, where a single well was tested in Luanda on one of the well of the Camelia reservoir.

The key findings from this feasibility study were that HPAM developed adequate viscosity in the saline water, with a concentration of 700 ppm active material. Mechanical degradation can be anticipated in surface facilities, and values from $25 - 50\%$ degradation were measured during tests through subsea well chokes. Adsorption in the reservoir remained low. Estimation of incremental oil recovery was found to be $3 - 7\%$, depending on the system and on the start date of polymer injection.

2.6.2.2 Injectivity test

The tested skid was installed and ready for use on the DALIA FPSO by the end of December 2008. The polymer injection at Dalia started in January 2009, after an integrated geosciences and architecture study. After a successive injectivity pilot in Luanda, additional single well injectivity tests were performed in 2009 on three Dalia wells with different configurations.

2.6.2.3 Injection at Dalia

The powder polymer process unit (skid) was installed on the FPSO, rather than on a boat/barge. The injection of polymer at the Dalia field is prepared in two steps. In the first step the mother solution is prepared from desulfated water, and matured during a 30 min to 1 hour period. The use of desulfated water is to avoid barium sulphate scaling. After the mature period, the solution is injected under pressure (max 50 bar) into the injection water system for dilution through a static mixer. The diluted solution is then sent to the riser. For the skid used at Dalia, maximum capacity is 21 m^3/h of high concentration solution at 9000 ppm. Higher concentration can also be prepared, but at a lower rate, which makes the dilution in the static mixer more difficult to achieve.

The initial diluted concentration of 700 ppm was increased to 900 ppm after the injectivity test, to achieve the design viscosity of 3.5 cP at top of the riser. This corresponds to a viscosity of 2.9 cP at reservoir conditions (taking into account low temperature, and some degradation of the polymer through process and the transit through the choke at the subsea Christmas level). The skid was tested to produce 200 m^3/h viscosified water with a polymer concentration of 900 ppm.

The polymer used to make the mother solution is supplied in 750 kg bags. They are imported from Europe and stored on shore in Luanda. Shuttle boats deliver the polymer bags to the FPSO. The bags are emptied into a silo at FPSO through a pneumatic transfer with a combination of both transfer screw and dry air blowing.

From the silo, the polymer is transferred to a feeding storage tank which is called the weighing hopper. From the storage tank, the polymer solution is dosed with a regulated screw and poured into a grinding machine called the powder slicing unit (PSU). Here the solution is brought in contact with desulfated sea water with characteristics of 29 g/l salinity, no oxygen and no bacteria. A combination of produced water and desulfated seawater is used as dilution water to make up the required injected solution, before the solution is transferred to the maturation tanks. Behind the dosing screw outlet, a nitrogen blanketing and nitrogen injection is in place. This is required for two reasons:

1. To maintain the integrity of the injection line on the sea floor since it is made of carbon steel.
2. To prevent the risk of oxidation reaction of polymer with Fe ions.

Also, because of these reasons, the oxygen concentration in the solution must be below 30 ppb. The pressure is raised to the injection level by a triplex pump. Significant degradation may occur in this pump.

2.6.2.4 *Operational results of the injectivity test*
The test started 24 December 2008 and ended 3 April 2009 on well DAL710. The test showed good results, the polymer solution prepared on the FPSO was of good quality, filterability was good (FR <1.1), the insoluble content was low (<0.5%) and the oxygen content was below 10 ppb. A pressure drop measurement upstream and downstream of the subsea well choke recorded a change in pressure drop from pure water to polymer solution.
The target viscosity was 3.3 and 5.6 cP at the riser head, and this was achieved by an injection rate of 13000 and 12000 bwpd respectively. The injected volume was 390000 barrels above 3.3 cP.

2.6.2.5 *Phase 1*
After the injectivity test on the single well was successfully completed, a period of only water injection was initiated. This was done for different objectives:

1. Measure the pressure behavior of DAL710 after polymer injection
2. Establish a water injection base line for the other two injectors DAL713 and DAL729
3. Inject a tracer ahead of the polymer front in each of the three injector wells of Camelia

Phase 1 started on 8 February 2010. By June 2010 3.284 million barrels of polymer solution had been injected in the three wells on the line (DAL710, DAL713 and DAL729). Pressure monitoring indicated that the injectivity was still excellent even though high volume of polymer was injected. The quality of the solution remained in line with specifications, and there were a low filter ratio (1.1) and low insoluble content (0.5%).

On sites studies were also done after the water injection period. The studies were done to characterize the stirring efficiency, the maturation evolution in the tanks, the mechanical

degradation of the solution through HP pump and static mixer, and chemical degradation of the diluted solution.

The promising results from the injectivity test and phase 1 have opened the door to other polymer injection projects.

2.7 State of the art – Polymer Injection

There are state of the art technologies which are suitable for polymer injection and flow control. These systems often comprise a fluid flow controller, especially at the injection sites, since it is at these sites most of the degradation of polymer flow occurs. Chokes is the most common flow control device used, but because polymers are "shear-thinning", such chokes damage the polymer, hence reduces the viscosity of the injected polymer fluid [23]. The shearing of polymer in chokes occurs due to immediate pressure drop and extreme velocity when the fluid passes through the orifice. It has been found that if the pressure drop is reduced over several stages or over a longer length (like a spiral), then the polymer is less damaged and degraded. There are several patented technologies with these concepts. In the sub chapters below, there is a brief description of some state of the art in polymer injection and polymer flooding.

2.7.1 Injection-point flow control of undamaged polymer

The present invention by Dyck (2011) [24] refers to a device that gradually regulates and controls the flow of injected polymer flooding EOR fluids at every injection points, without damaging the polymer fluid. The device contains a conduit with variable length paths and with centrifugal forces or other retarding or decelerated forces. The conduit is accessible to the operator, which then can easily configurate or arrange the spiral orientation, and the relative position of each section of the conduit. A non-destructive flow control within a compact space is attained.

The embodiments of the present invention include a device which in non-destructive way controls the flow of polymer flooding EOR fluids at the injection into a well-site.

This device may provide synchronized multiple flow control over a polymer flood. Multiple polymer wave fronts can be coordinated from different directions to arrive in timely manner acting on a common production point. With this, a flooding plan is implemented, which in an effective manner makes the optimal use of a compact apparatus. The apparatus contains tightly configured seamless conduits and smoothly joined elements which avoid inducing turbulence. The polymer fluid is passed through coils of pipework which are densely assembled in close proximity, with matching internally machine fittings wherever they are required. This allow for continuous deceleration without turbulence.

The flow of polymer fluid may be finely tuned to an injection point by the operator. The flow pattern of the site may be refined/customized such that a sufficient volume of polymer fluid is supplied to each high-resistance injection points, while limiting the volume of polymer flowing to low-resistance injection points. The polymer fluid is by this delivered to all

injection points, without being degraded, and are then able to sweep out more oil from the reservoir. The polymer fluid will synchronously travel through their respective flow controllers and their respective portions of the formation before it arrives at their designated location in a timely manner. This combined sweeping effect of polymer fluid may move oil through the reservoir and towards a common production point in a more efficient manner, without fingering of water or breakthrough. It is preferred to install the device at each injection point, such that the flow can be individually controlled without inducing turbulence. It is possible for the operator, by varying the effective length and spatial orientation of the drag inducing conduit, to control the volume of laminar flow of polymer fluid to a particular injection point. The polymer fluid is subjected to frictional drag; it adheres to the inner walls of the conduit. The polymer fluid is also subjected to decelerated forces. That is, forces that absorbs energy from the polymer stream when it changes direction, passing around each curve. Decelerated forces are especially enhanced by the use of helical structures such as a tubular coil. Excess energy is gradually dissipated, and turbulence is avoided. The low resistance injection points have longer, more frequent and tightly looped paths of conduits. This delays the arrival of the required volume of polymer fluid into the formation, such that the operator can more easily coordinate the delivery of polymer fluid into the high resistance injection points.

A compact device may also be provided, which can reliably adjust and control the flow rate at the injection point. The operator can introduce or omit different series of coils of different lengths by turning any or all of the bypass valves in the fluid circuit. The present device permit the operator to accommodate the fluid flow factors of viscosity, density, velocity, active conduit length, inner diameter of available conduit, internal roughness of conduit, transient changes in temperature, and the relative position of supply and discharge manifolds and lines. In addition, in takes into account and make is of centrifugal forces and other naturally decelerated forces of the combination of possible spatial orientations that are available. The device is also more compact, and takes up less space than other devices.

The polymer fluid must be delivered to each injection point without any shearing. One embodiment of the present invention uses a conduit which does not restrict the polymer, instead it introduces the required pressure reduction without exposing the polymer to sudden changes, and hence it does not get sheared. One embodiment of the present invention introduces resistance to flow by gradually reduce the velocity by adjusting the number of loops of pipe which increase back pressure (or drag) when the polymer flows through the loop. Several loops can be connected in series together with bypass valves. This permits each coil of tubing to be used alone. The back pressure of each loop or coil is created by the viscosity of the polymer flow as it resists flow. Typically, when a fluid flows through a tube, the fluid flows fastest in the middle, and slowest at the outer edge, near the tube walls. This creates a boundary layer in the fluid at the wall of the tubing, where the flow in negligible. This means, the only flow of fluid near the tube walls, is when molecules hop over each other. The faster moving fluid in the middle, near the slower moving fluid at the edge of the tubing can cause rolling of fluid molecules. Energy is also required to move the fluid when it

changes direction (accelerating around each coil) which causes a pressure loss when the fluid flows along the tubing.

The present device can be accommodated to local conditions, or it can address specific conditions at a given well-site where a particular injection plan has to be implemented. However, the apparatus is designed to control the flow of polymer fluid during injection into a well to enhance the recovery of oil from a production well.

The present apparatus consist of a inlet fluidly coupled to a source of polymer under pressure, to receive the polymer fluid, an outlet fluidly coupled to an injection point, and at least one conduit which provides a selective variable flow path length coupled between the inlet and outlet. The conduit must have internal friction, which creates a drag between the conduit and the polymer fluid, which controllably decelerate the rate of flow of the polymer fluid. Optionally, the apparatus may consist of at least one valve fluidly coupled to the conduit. The valves function is to control the length of the conduit through which the stream of moving polymer fluid pass, before it reaches the outlet. The conduit may include a first tube which is coupled to the inlet, and a second tube which is selectively coupled to the first tube and the outlet. The conduit may also include at least one valve which is selectively couples the second tube into and out of the flow path of polymer fluid, thereby controlling the length of the fluid flow path defined by the conduit. The apparatus may also include a bypass mechanism, which is able to divert the flow of polymer fluid to the outlet. To enhance the deceleration of polymer fluid within a more compact space, the first and second tube may comprise a helical coil or round tubing's or connected lengths of pipes. Optionally, the apparatus can include a heater and housing. This permits for injecting polymer fluid during cold weather. The present invention is illustrated in figure 2-2 below.
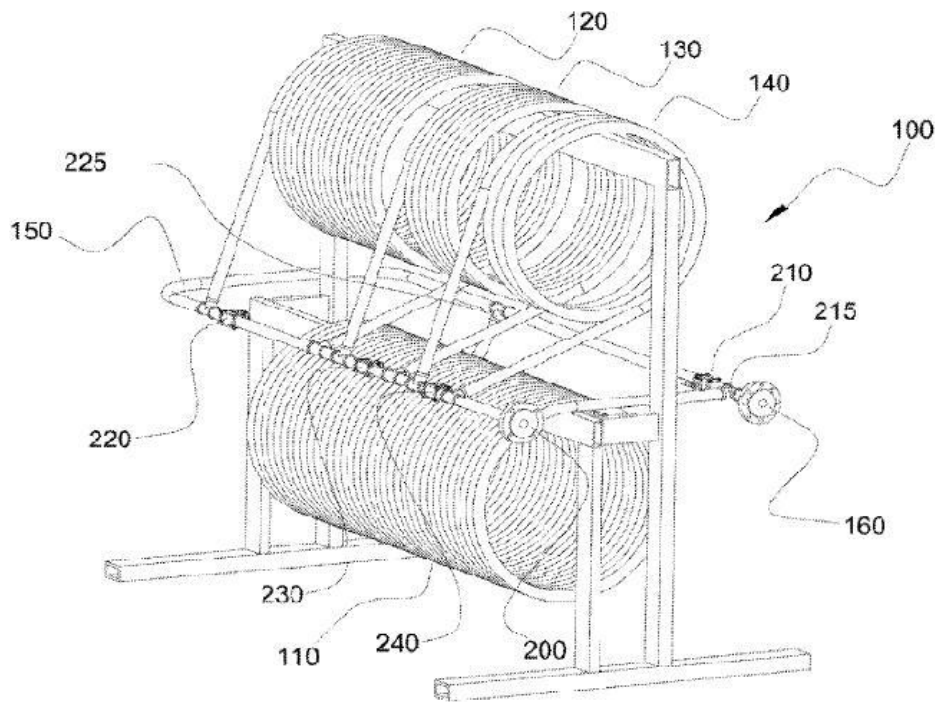
Figure 2-2: The present invention by Dyck

Figure 2-2 above is an isometric view of the compact apparatus (100) which controls the flow of a polymer stream. The illustrated apparatus consist of four coils of tubing forming a conduit, which provides a variable length flow path. The apparatus can be used to move a polymer stream in the laminar flow range, up to 25 cP viscosity, and is applied during injection to enhance oil recovery. A lower tube coil (110) is coupled to a bank of upper tube coils (120, 130, 140) of varying lengths, through a header (150). In this illustration, tube coil 110 is 160 feet long, tube coil 120 is 80 feet long, tube coil 130 is 40 feet long and tube coil 140 is 20 feet long. The header has an inlet (160) which receives the polymer fluid, and and oulet (200) that terminates the fluid flow. Isolation valves may be installed on either side of the inlet and the outlet.

A plurality of bypass valves (210, 220, 230 and 240) permits the operator to vary the length of the total conduit in which the polymer fluid flows between inlet and outlet. If bypass valve 210 is open, the polymer stream takes the path with the least resistance, flows through the header (150) without entering the lower tube (110). If bypass valve 210 is closed, the polymer fluid is then diverted at tee (T) coupling (215), through lower tube coil (110) and re-coupled to header (150) at tee (T) coupling (225). From here, the polymer fluid flows through the apparatus, and out through the outlet. If bypass valve 220 is open, the stream of polymer fluid bypasses tube coils 120. If bypass valve 220 is closed, then the polymer stream is diverted through tube coil 120. When bypass valves 230 and 240 are open, the polymer stream bypasses their respective coils 120 and 140. When they are closed, these valves can be used by the operator to increase the drag inducing path length. With these bypass valves; the laminar flow stream may be slowed down without any harmful turbulence.

The conduit may be of any cross-section and does not have to be restricted to tubular coils. The coils may take any form, and may have square or rectangular cross-sections. However, there may be easier to carry out mathematical determination if the coils are tubular, because this is more familiar.

2.7.2 *Low shear polymer injection method with ratio control between wells*

The present invention by Stalder (1980) [25] is a method for injection of shear degradable aqueous polymer solution into a polymer flood for enhanced oil recovery. A series of pumps are used in a multi-branch system. The pumps are maintaining pressure and flow rate control, while they reduces shear degradation of the polymer solution. The pumps are driven by hydraulic drivers, wherein the hydraulic power source for the drivers is controlled by a pressure sensing loop and a rate proportioning loop. In the pressure sensing loop, a selected preset pressure will not be exceeded by any branch of the injection system. In the proportioning control loop, the injection rate in the various branches will be maintained in a given proportion to one another, regardless of changes in the rate in the injection system, or in a master branch.

Polymer degradation due to mechanical shearing is reduced by the use of plunger pumps, or other low shear pumps like diaphragm pumps and progress cavity pumps. For the hydraulic oil system, throttle valves or hydraulic pumps are used.

The present invention is a method of maintaining ratio control with pressure override in a low shear injection system. A hydraulic oil system is used to drive the individual hydraulic motors which are connected to low shear pumps. They are all connected to a feedback system, such that all the individual pump rates are held in a automatically fixed proportion with pressure override compensation, regardless of rate variations in the system.

The main object of the present invention is to provide a method which allow for ratio control with pressure override together with low shear rate injection. Further, it is a object to provide an automated rate proportioning and pressure override control on injection fluid with separated pumps used on various injection streams. An illustration of the present invention is given below in figure 2-3..
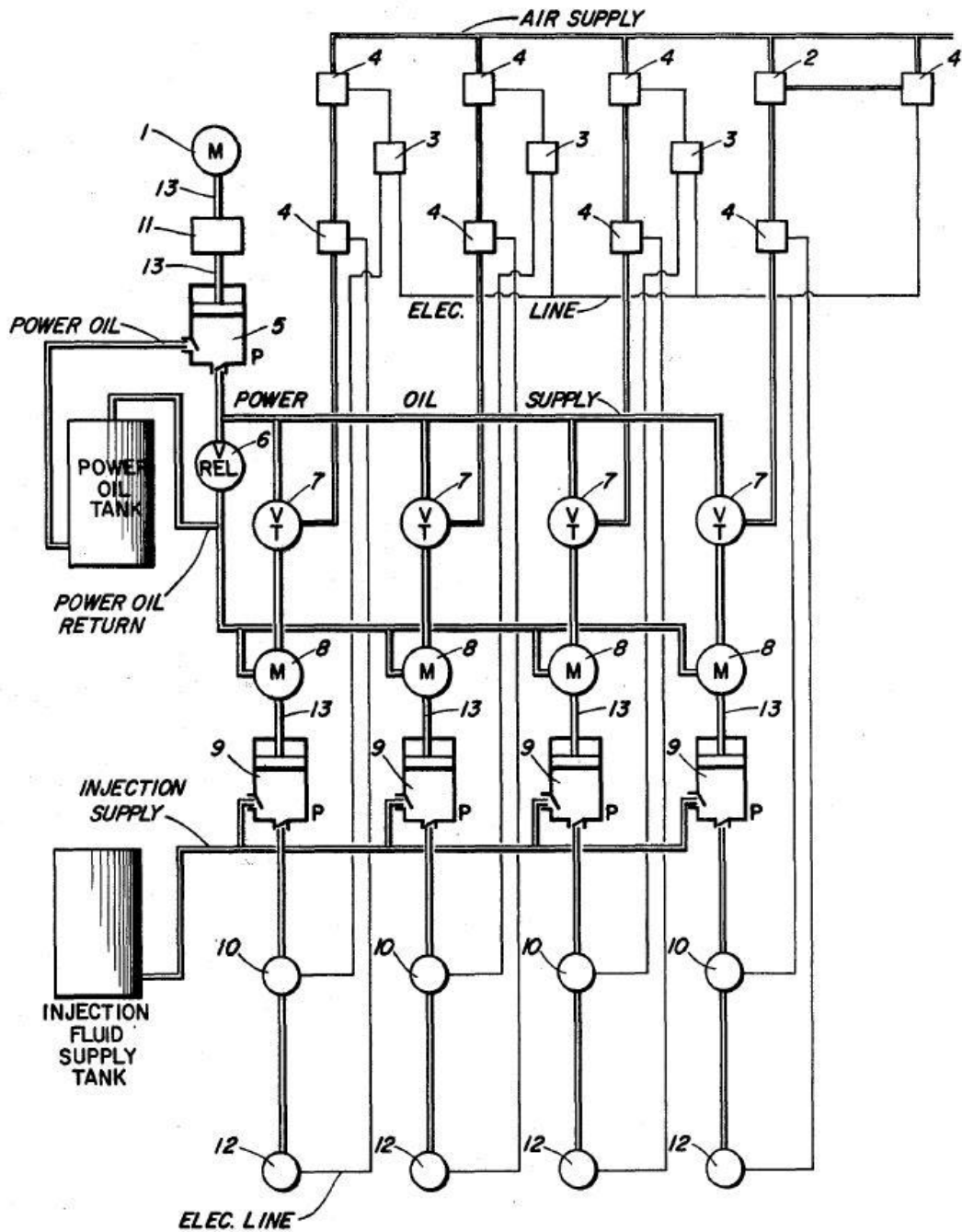
Figure 2-3: The present invention by Stalder (1980)

With reference to figure 2-3, which is a schematic of the multi-branch system having three branches, in addition to a master control injection well? The number of branches can be varied in order to fit the needs for a particular situation. The system is briefly described below.

An electric motor (1) is the power source for the entire system. The electric motor drives a shaft (13) which operates a hydraulic power oil pump (5), which circulates power oil trough the system and the power oil reservoir. The power oil travels from the pump through throttle valves (7) and from there into a hydraulic motor (8). After the oil has passed through the

motor, it returns to the power oil tank for recirculating. The shaft (13) transmits power from the hydraulic motors to low shear pumps (9). As notes, these pumps may be plunger pumps, diaphragm pumps or progressive cavity pumps. The pumps receive an injection fluid from a fluid reservoir, and inject the fluid through a turbine meter system (10). These turbine meters have frequency outputs which can be converted to analogue outputs. This is carried out by the use of a frequency or current (or pneumatic) converter. From the turbine meter system, the fluid passes into the injection well. Here, a pressure sensor (12) converts the sensed pressure into an electrical current. Simultaneously, an air supply passes through a conduit and to a pneumatic converter (4). The pneumatic converter (4) is controlled by a ratio controller (3), which receives the analogue output from the turbine meter (10). With this, the ratio controller adjusts the flow or air controls the throttle valve which regulates the hydraulic flow to the motors. The reading of the analogue output by the ratio controller is the primary rate control. The pneumatic converter (4) reads electrical currents produced from the pressure sensor (12). If the preset pressure on the pneumatic controller (4) is exceeded, the pneumatic converter (4) throttles back the amount of power oil flowing through the throttle valve (7). The ratio controller (3) operates only from the rate input derived from the various turbine meters. In the turbine meters, frequency outputs are converted to analogue by the use of a frequency-to-current or pneumatic converter. By adjusting the hydraulic flow through the throttle valve (7), the power flow is adjusted.

The present system powers hydraulic motors which operates through drive shafts (13), and controls the low shear pumps (9). This allows for adequate control of polymer rate and pressure in the wells, while maintaining low shear degradation of the polymer solution. Further, this system will solve the problem of shear degraded polymer providing automated rate proportioning and pressure overriding control of the polymer fluid, with separated pumps on each injection stream.

2.7.3   *Non-shearing polymer flow control*

Ken Krewulak of Canadian Natural Resources is one among others that has found that the degradation of polymer in polymer injection can be reduced if the pressure drop is extended over a longer length [23]. A small diameter pipe may be used, to utilize the pipe wall friction. From the testing, it was found that ½" pipe was the smallest diameter that would not shear the polymer at injection rates up to 175 m^3/day. Also, it was discovered that a flow rate of 150 m^3/day with a 1500 ppm polymer solution, a pressure drop of 22 kPa/meter was imposed. The device is illustrated in figure 2-4 below.
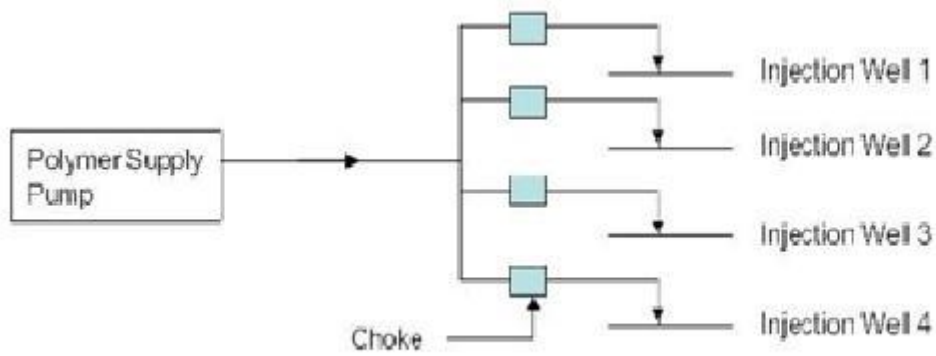
Figure 2-4: the present device for reduced polymer degradation by Ken Krewulak

The illustrated device was constructed with a total length of 620 feet, which corresponds to 190 m of ½" pipe. The device was designed with a back pressure of 4500 kPa, at a flow rate of 150 $m^3/$ and with a polymer solution of 1500 ppm. Five coils with different lengths were fabricated. This allowed for the flow to be changed from 620' down to 0' in 20' increments. The flow length was changed by the use of a valve, which was either opened or closed in order to achieve the desired pressure drop and flow rate. A schematic illustration, as well as a picture of the present device is shown in figure 2-5 below.
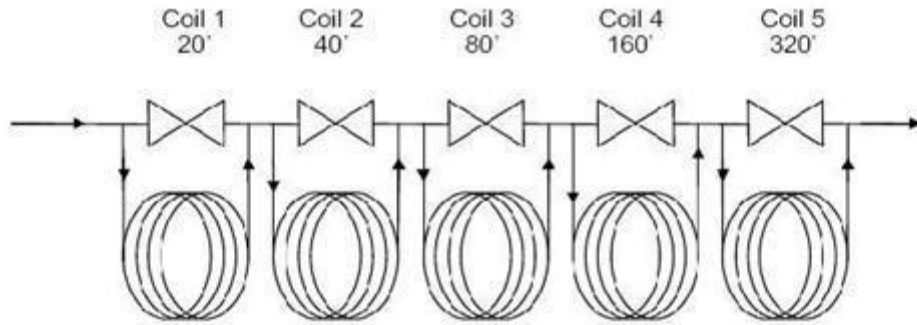
Figure 2-5: A schematic illustration as well as a picture of the present device by Ken Krewulak

Multiple tests have been carried out, and the device has proven to be very effective at controlling the flow of polymer without inducing shear. It was found that the viscosity of the polymer solution entering the device was the same as the viscosity of the polymer solution leaving the device. This means that minimal degradation of the polymer occurred.

2.8 Shear stress and Mechanical degradation

There have been successful field experiences with polymer flooding, like the ones described in chapter 2.6.1 and 2.6.2, however, there have also been much problems associated with polymer flooding, as well as ineffective and unsuccessful attempts. The main problem is that polymers undergo mechanical degradation in mechanical facilities like valves and pumps which is to be found in a polymer injection skid, and also in the reservoir which typically have a shear rate of $5 - 10$ s^{-1} [26]. Degradation of polymers results in loss of viscosity, and ineffective sweeping of oil. It is outermost important to try to minimize degradation of

polymers during injection and flooding, in order to keep the mobility ratio low, such that more oil can be swept out.

With reference to figure 2-6 below, standard valves may me responsible for up to 70 % degradation of the polymer solution [27], depending on the pressure drop through the valve. As the pressure increases, the more degradation of the polymer solution occurs.
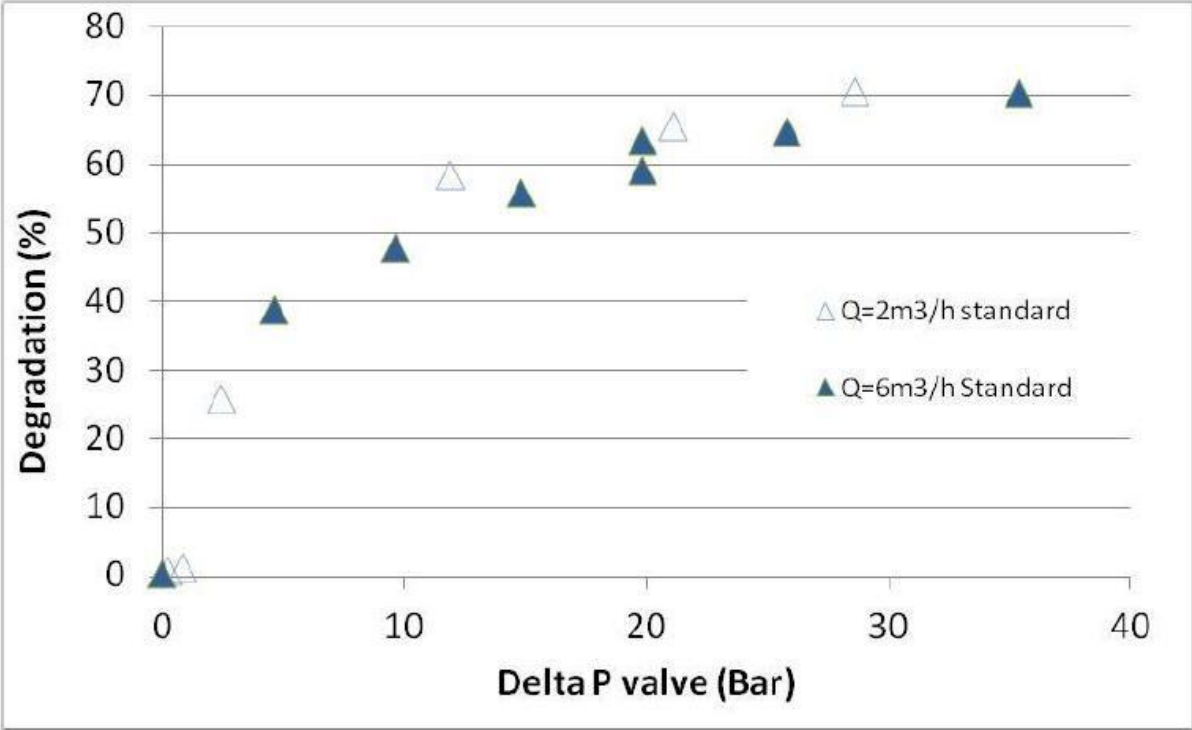
Figure 2-6: Degradation with Standard Valve

As noted in chapter 2.1, up to 20% viscosity loss is acceptable, but higher viscosity loss may comprise the project. Standard valves are therefore not suitable for polymer injection, because they degrade the polymer solution to a greater extent than what is acceptable for a successful flooding to occur.

It is to believe that a valve which causes severe droplet break-up also may cause severe degradation of polymer solutions. Droplet break-up in valves are a function of the energy dissipation unit, E [28], which is dissipated in the volume within the valve. Dissipating the energy within a small volume creates massive turbulence, hence more shear. In conventional valves, the volume which is involved in dissipating the pressure energy within in the valve is to low. Dissipating pressure energy within a greater volume is found to reduce droplet break-up. The key difference between the Typhoon Valve and other conventional valves is the larger volume in the Typhoon valve where E can be dissipated, which reduces the turbulence, hence less shear is created.

Further, it is to believe that other low shear technologies, especially with the use of coils and pipes like the Typhonix's fluid flow device (Shark) will reduce mechanical degradation. Coils

and pipes can be adjusted such that the pressure gradient is taken over a longer length than with a conventional valve, and Ken Krewulak has proven that this has a positive effect of mechanical degradation of polymer solutions (chapter 2.7.3). It has been seen that degradation of polymer strongly depends on ΔP, and with higher pressure, more degradation of the polymer solution occurs (Figure 2-6) [27]. It has also been documented through a bachelor thesis, see chapter 3.9 and A5, that these coils have a positive effect on oil in water emulsion, so it is to believe that the same coils will have a positive effect on mechanical degradation of polymers.

The energy dissipation unit is described in more detail in chapter 3.2. Low shear technologies and valves are described in the following chapters.

3   *VALVE TECHNOLOGIES*

Besides polymer injection technologies, there are also valves which may be suitable for polymer injection. Valves are one of most used devices in petroleum production. They are specifically designed to direct, stop, start, mix and regulate the flow, pressure and temperature of a process fluid [28]. If the valve acts as a restriction, energy of the process fluid may be transformed from one state to another. Transformation of energy, the energy dissipation is inevitable when it comes to regulation of a fluids pressure or flow rate. It is the energy dissipation which is the mechanism of regulation. A negative side effect of pressure and flow regulation is often emulsification and droplet break-up, which means more dispersed phases and smaller droplets. This complicates the downstream separation process and degrades the end product.

3.1   *Regulation valves in petroleum production*

There are numerous valves in the petroleum processing plant which regulates flow rate and pressure [28]. Throttling valves are valves that regulate the flow by execute a restriction to the flow. They are typically used to regulate flow rate, pressure and temperature in a process plant. A throttling valve that is used to regulate the flow from a well is termed choke valve, while control valves are the ones that regulates the flow between process equipment. Choke valves has in principle three different functions. The first and main function is to regulate the rate of production of a natural flowing well stream. This is to ensure that the reservoir is produced at the most efficient rate, where gas and water coning is prevented, as well as problems associated with sand production. The second function is to reduce the pressure of the fluid down to an acceptable level. The third and last function is additional and desirable effect of isolating the upstream a downstream process system from each other, which is achieved when the flow in the valve becomes choked. A liquid flow becomes choked under certain conditions involving high differential pressure and cavitation or flashing. A gas flow is choked when the velocity of the fluid reaches the velocity of sound. When the flow is choked, the upstream pressure is not affected by the downstream pressure, and the valve ensures stable production rates and reservoir conditions, independent of varying downstream process conditions.

Choke and control valves have in common that they represent a restriction to the flow in the pipes. A valve always as the available flow area in the valve is altered, independent on valve structure or internals. The flow is gradually increased as the valve is operated from a fully closed to a fully open position, even though the flow area is fixed in a choke. It is geometry of the valve internals that regulates how the flow rate varies according to the valve position.

3.2   *Droplet break-up in Valves*

Regulation valves extracts energy from the turbulent flow [28]. The energy dissipation rate in a control volume in a duct flow equals the differential pressure across the control volume

multiplied by the flow rate through it. If the control volume for a given valve is defined, the energy dissipation rate is given by equation 3.1.

$$É = \Delta p_{perm} . Q \qquad\qquad (3.1)$$

Where:
Δp_{perm} = Permanent pressure drop across orifice
Q = Flow rate

Normally, the energy dissipation rate $É$ may be found for a valve operating at specific conditions. However, the extension of the zone where most energy is dissipated is typically unknown. In laboratory studies, the extension of the zone has been determined by flow through a circular orifice. Most of the turbulent energy is produced downstream the orifice in a volume of a radial extension which corresponds to the radius of the orifice and to e certain axial extension. If it is assumed that all the turbulent energy in immediately transferred into heat in this volume, the volume V_{dis} of energy dissipation, the dissipation zone, is given by equation 3.2.

$$V_{dis} = A_0 . L_{dis} \qquad\qquad (3.2)$$

Where:
A_0 = Cross sectional area
L_{dis} = Axial length of dissipation zone

If the dissipation zone V_{dis} is multiplied with the fluid density p, the mass of the fluid in the dissipation zone can be given. The mean energy-dissipation rate per unit mass, ε, in the dissipation zone downstream of an orifice is expressed as equation 3.3.

$$\varepsilon = \frac{É}{p . A_0 . L_{dis}} \frac{\Delta P_{perm} . Q}{p . A_0 . L_{dis}} \frac{\Delta P_{perm} . U_0}{p . L_{dis}} \qquad\qquad (3.3)$$

Where:
U_0 = Mean fluid velocity in orifice

In turbulent flow, the maximum droplet size is expressed as equation 3.4.

$$d_{max} = We_{crit}{}^{3\,5} \; \frac{\sigma}{p_c} \; \varepsilon^{-2\,5} \qquad\qquad (3.4)$$

Where:
$Wcrit$ = Critical Weber number (constant)
σ = Interfacial tension between dispersed and continuous phase
p_c = Continuous phase density

From this equation, it is shown that the maximum droplet size depends strongly on ε, which basically is the turbulence in the valve. The intensity of turbulence is also proportional to the pressure drop across the valve.

3.3 Low Shear Typhoon Valve

3.3.1 Technology Background
Valves are one of the most used equipment during petroleum production and processing. The objective of a processing plant is to separate produced oil, water and gas into clean phases, as illustrated in figure 3-1 below [29].

Figure 3-1: Illustration of petroleum processing, the produced fluids are separated into clean phases

One on the main problem with conventional chokes and control valves is that they mix and emulsify the fluid phases, which have a negative effect on the downstream separation. The result is poorer water and oil quality. After separation, the produced water is often discharged to the sea. To reduce the environmental impact and to meet the stringent governmental discharge criteria for produced water, mechanical and/or chemical treatment is often required. As a field matures, more water is coproduced with the hydrocarbons, which means that more water has to be treated before discharge. Typhoon valve, which is a low shear choke valve, reduces mixing of the petroleum phases as well as droplet-break up [28]. The result is improved separation of oil water and gas, especially has the valve a promising effect on the produced water quality.

3.3.2 Concept and Potential
The new valve concept in Typhoon Valve is developed mainly to reduce droplet break-up and emulsification of fluid phases in valves. The valve technology is especially intended for petroleum processes, which gain large benefits from reduced droplet break-up. The cyclonic principles used in Typhoon Valve confer general advantages over a conventional valve, with the advantages being [28]:

- Less droplet break-up
- Less cavitation

- Less erosion
- Less vibration
- Less noise

There are other low-shear valves, but Typhoon Valve confers additional benefits over these because of the characteristic vortex flow. The additional benefits over other low-shear valves are:

- Being and infinite multi-stage valve
- Facilitating coalescence rather than droplet break-up
- Choking

The pressure in a Typhoon Valve is gradually reduced, which means that the valve can be considered as an infinite multi-stage valve. In addition, the vortex flow in a Typhoon Valve creates a flow structure enhancing coalescence rather than droplet break-up. The reason why is because the dispersed phase in a continuous fluid phase will be concentrated in the vortex flow in the cyclone. If the dispersed phase is the lighter phase, the concentration will happen at the cyclone center. If the dispersed phase is the heavy phase, the concentration will happen at the cyclone wall. The consequence is that droplets of a dispersed phase will become enlarged in the Typhoon valve, while the opposite is the case in other low-shear valves or conventional valves. Other low-shear valves may reduce the velocity and droplet break-up, but they miss one important valve feature, they can not choke the flow that means, and they can not isolate the reservoir from the process plant. In the Typhoon Valve the fluid mechanisms is different, and choking is possible.

As noted, Typhoon Valve is especially developed for the petroleum industry. Used in a process plant a Typhoon Valve will lead to:

- Significantly improved efficiency of oil-water separation
- Reduced amount of oil in produced water
- Reduced amount of water in oil
- Reduced use of production chemicals
- Increased effect from use of chemicals
- Reduced maintenance cost
- Improved working conditions

When the pressure drop across a Typhoon Valve and a conventional valve is equal, the velocities in a Typhoon valve are less, and the consequence is minimized or eliminated droplet break-up and emulsification. The Typhoon Valve has a different flow structure, which is the reason why this valve has significantly lower shear forces compared to traditional valves. Other disadvantages associated with conventional valves are also minimized due to lower velocity and shear forces. Disadvantages like cavitation, erosion, vibration and noise is reduced.

3.3.2.1 Concept

The Typhoon Valve uses cyclonic flow in contrast to generic orifice-based conventional choke and control valves [2]. The internals in a Typhoon Valve is illustrated in figure 3-2 below, and includes:

1. A cage with tangentially oriented orifices
2. A venturi-shaped cyclonic body
3. A vortex breaker
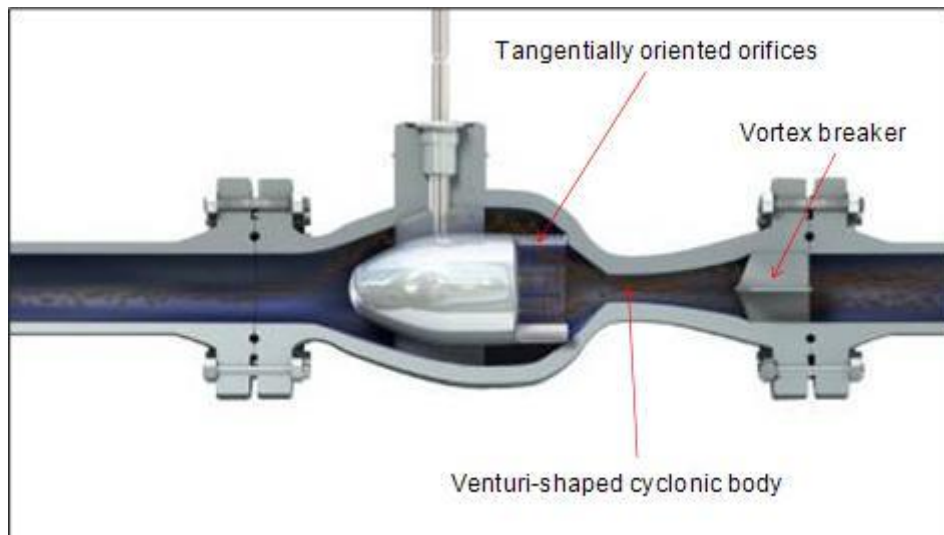
Figure 3-2: Typhoon Valve principles

The cage has tangentially oriented orifices which regulates and transform the axial inlet into a vortex flow. The vortex flow created by the cage results in less shear forces and turbulence compared to the flow in conventional valves. The cyclonic body creates a vortex pressure drop over several stages, and the vortex breaker transform the vortex flow into axial outlet flow. The consequence is less shear forces and less turbulence, this result in less mixing of petroleum phases and better downstream separation.

Figure 3-3 below shows the principles of both the Typhoon Valve and a conventional valve. The Typhoon valve uses the principles of a vortex to control petroleum flows [2]. This involves a larger fluid volume in dissipating energy, which is required to control the flow. The effect of a two phase flow is also illustrated for both the Typhoon valve, and a conventional throttling valve.
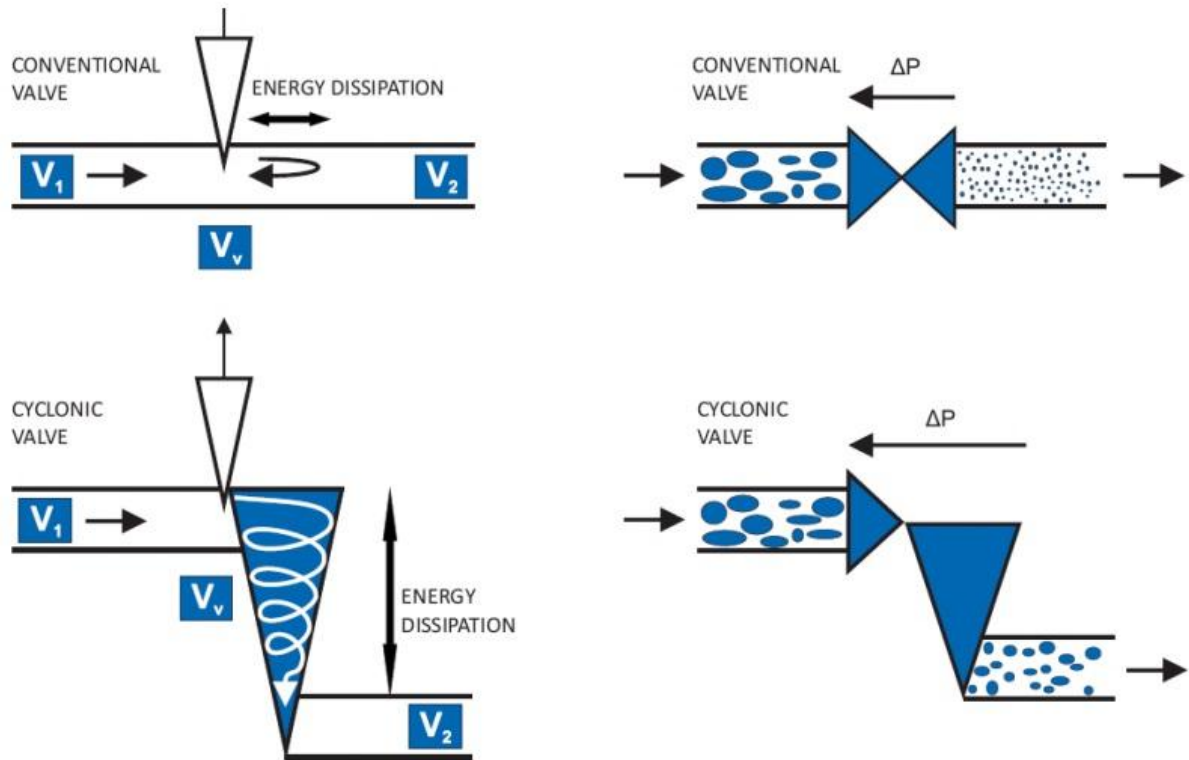
Figure 3-3: The principle of the cyclonic Typhoon valve compared to a conventional valve

It is documented through laboratory and full scale experiments that Typhoon valve is a separation friendly and low-shear valve. The low-shear valve may reduce the degradation of polymers. Turbulence is the sole mechanism for polymer degradation, and with the Typhoon valve the turbulence will be minimized, hence gives less degradation.

The less shear forces and turbulence provided by the Typhoon Valve may be taken advantage of in polymer flooding, thus creating less degradation of the polymer and higher recovery of OOIP.

3.3.3 Typhoon valve development and Pilot project

The Typhoon valve is a cyclonic low shear valve, which due to less pressure drop in the valve reduces mixing of oil and water, in addition to reduced droplet break-up [2]. The result is enhanced separation of petroleum phases, reduced fluid mixing as well as reduced emulsion viscosity. The development of the Typhoon Valve started in 2006 through a PhD study at the University of Stavanger. Since then, the Typhoon Valve has been tested in large and small flow rigs, with different crudes and parameters, and the separation benefits of the valve has been established.

The development of the Typhoon Valve has consisted of three subsequent projects
1) The Typhoon Valve Feasibility study (concluded 2006)
2) The Typhoon Valve development Project (concluded 2009)
3) The Pilot Installation and Testing of Typhoon Valve (ongoing)

3.3.3.1 The Typhoon Valve Feasibility Study (2006)

The concept behind the Typhoon Valve was a part of a PhD study done at the University of Stavanger. Through this study, it was concluded that cyclones have a potential for reducing droplet break-up and reduced phase emulsification during petroleum flow control. Based on the result of this PhD study, a feasibility study was suggested. The participants and the finance of the project were ConocoPhillips, Statoil, Shell and the Research Council of Norway. The objective of the study was to elaborate the realism and possibility of developing a cyclonic valve for petroleum operations. It was concluded, through the feasibility study, that the Typhoon Valve may replace any petroleum regulation valves, with the greatest separation benefits as a choke valve. Also, due to its size and weight estimate, the conclusion was that the Typhoon Valve was a realistic alternative for choke valve applications.

3.3.3.2 The Typhoon Valve Development Project (2007-2009)

The conclusions and findings from the feasibility study led to the Typhoon Valve development Project in 2007. This project was financed by ConocoPhillips, Statoil, Shell, Eni, Total, Mokveld and the Research Council of Norway. A three phase testing at the Exxsol test loop of MPM in Stavanger was the first conducted experiment with the Typhoon Valve. A small scale Typhoon Valve was tested with a number of different geometries, and at various test conditions. The conclusion was a positive effect on oil/water separation. Even with large changes in the Typhoon Valve geometry, the positive separation effect remained unchanged. Further, it was found that the positive effect of Typhoon Valve is a strong function of water cut, and that Typhoon Valve enhances both oil and water quality.

The second study in the development project was a screening study. Here, a small scale Typhoon Valve was used, with 9 different North Sea crudes [4, 5]. The objective was to investigate relative differences and compare the influence of Typhoon Valve and a standard valve on oil and water quality for the nine different crudes. The crudes that were used were Ekofisk, Gullfaks C, Troll B, Heidrun, Draugen, Grane, Norne, Valhall and Goliat. Based on this test, and a produced water test with the prototype Typhoon Valve, it was concluded that Typhoon Valve has a systematic positive effect for all crudes. Comparison of the median oil droplets between Typhoon Valve and a standard valve, showed that the median oil droplets downstream Typhoon Valve were twice the size. From separation studies at three different water cuts, it was concluded that Typhoon Valve has a positive effect on both oil and water quality for seven of the nine crudes that were tested.

The Development Project was concluded in 2009 with a prototype test in Porsgrunn. The Typhoon Valve was tested at realistic process and flow conditions. Gullfaks crude oil was used, in addition to natural gas at high temperatures and pressures. The main purpose of the prototype test was to study the effect of Typhoon Valve and a standard valve on oil/water separation in a downstream pipe-separator. The process conditions were water cuts from 10 to 90%, valve pressure drops from 4 to 10 bar, gas/liquid ratios from 0.1 to 0.5 and different Typhoon Valve geometries. The testing was done in close cooperation with Mator, as well as analysis and evaluation of the results. The conclusion from the prototype test was that Typhoon Valve has a significant effect on the produced water quality. Reduction of oil in

water of 50 to 90% was achieved with water cut range from 50 to 90%. However, the effect on oil quality was somewhat uncertain. An illustration of produced water samples for Typhoon Valve (right) and a standard valve (left) is shown in figure 3-4 below, as well as the installation of the two valves in the test rig at Porsgrunn.
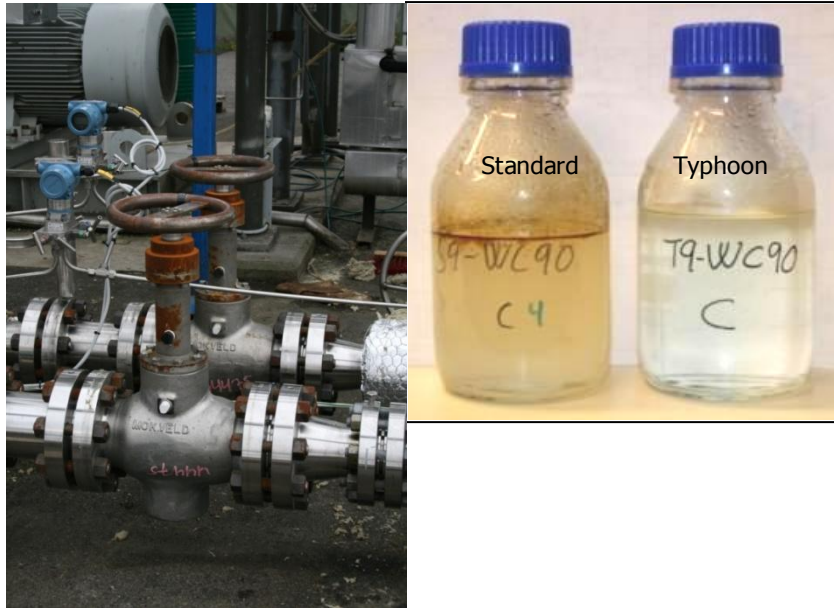
Figure 3-4: Left: Typhoon Valve prototype installed in Statoil's multi phase flow loop in Porsgrunn in 2009

3.3.3.3 *Pilot Installation and Testing at Oseberg C (concluded 2012)*

The decision to perform a pilot installation was based on the positive results from the feasibility study and development project. The participants and financers of the Pilot Project are ConocoPhillips, Statoil, Eni Norge, Total, Mokveld and Petromaks. One of the first activities that were done was erosion testing at GL Flow Centre in UK in 2009. However, the main objective is to test Typhoon Valve as a choke valve on oil producing well at a North Sea platform. The purpose of the test is to verify the downstream separation benefits from using Typhoon Valve, compared to a standard valve. The pilot test was carried out in the period of 12-23 March 2012. Well C-03 on Oseberg C was chosen to produce to the test separator during the test period.

Oseberg C was one among other candidates for a pilot test. The main reason why Oseberg C was the most appropriate option was due to its favorable water cut of approximately 75%, as well as evaluation of flow rates and gas/liquid ratios made Oseberg C the best decision. Evaluation of HSE aspects and HAZOP analysis were performed by Typhonix together with Mokveld and Statoil. The pilot valve has been manufactured by the valve producers Mokveld, in accordance to applicable standards and specifications. Mokveld was also responsible for planning of the valve replacement offshore. Typhonix was responsible for production of the vortex breaker, as well as the vibration and noise measurments during the pilot test. KANFA Mator was responsible for the test program, the fluid sampling and analysis during the pilot test.

3.3.3.4 Development of a Typhoon Subsea Valve (2009-ongoing)

This project started in 2009, and is ongoing. The main object of the Subsea Typhoon Valve project is to study and document the long term effect of Typhoon Valve on downstream separation and transportation processes [29]. For this reason, a three hundred meter long flow loop has been build, and tests with both light and heavy crude has been carried out. Activities done in this project has also been critically important in realizing the Pilot Test on Oseberg C: A second round of erosion testing at GL flow centre UK, with hardened internals in Typhoon Valve demonstrated a satisfactory erosion resistance. Geometry optimization and work done on the Typhoon Valve capacity model in the Subsea Typhoon Valve project were also relevant and important for the design and construction of the Pilot Typhoon Valve. The financers and participants in the Subsea Typhoon Valve project are EniNorge, Mokveld and the Research Council of Norway.

3.3.4 Possible Typhoon Valve benefits

Based on results of the Typhoon Valve development program it is made reasonable that Typhoon Valve, when used as a choke or control valve in a petroleum production and processing system, provides processing and separation benefits [2, 29]:

Generally,

- Typhoon Valve may improve the processing capability and increase the process' tolerance against upset and fluctuating conditions.
- Separation may be improved without resorting to additional mechanical or chemical treatment processes.
- Typhoon Valve may contribute to a cost effective and environmentally friendly separation process.

Specifically,

- Typhoon Valve gives less oil in re-injected or discharged produced water.
- Typhoon Valve may result in less water in exported oil.
- Typhoon Valve may reduce the amount of process chemicals:
    - ➢ Emulsion breaker
    - ➢ Flocculants
    - ➢ Anti foam

3.4 Background for the Typhoon Valve

Besides the Typhoon Valve, there are also other patents of low shear valves, with some of the same technology and concepts as the Typhoon valve. Below is a short review on cyclonic valves used in fluid control, and other low shear valves/technologies. The background for the Typhoon Valve is other low shear valves/technologies which are the Twister swirl valve [31], the Kouba valve [32], an adjustable flow rate controller [33] and a cyclonic valve [36]. In

addition has the Delft University of Technologies made some modifications on a choke, so it should become more separation friendly [34]. A short review of these patents will be given here, for a full review on the background for the Typhoon Valve, see appendix chapter A2 in Appendix A.

3.4.1 Potential Low-Droplet Break Up Valves – Multistage and Cyclonic valves

3.4.1.1 Multistage Low Velocity Valves

Multistage valves are globe type valves in which the pressure drop across the valve is developed over several stages, and with special retainers or cages [28]. The principle of operation is one or a combination of tortuous-path, pressure-drop staging or expanded flow areas. The effect of multi-staging is that the velocities in valve are reduced, hence the drawback related to high velocities are reduced. Even though a multistage valve is a low velocity valve, they come to short by means of a choke valve. The disadvantage is that they can not isolate the upstream side from the downstream by means of choked flow, the velocity is not increased enough to choke the flow. However, it is to believe that this type of valve will reduce droplet break-up, even though there are not any valves commercially available today that are developed solely to reduce this problem.

In addition to phase dispersion and droplet break-up associated with the high velocities in regulation and throttle valves, erosion is also a consequence of, and proportional to the fluid velocity, and the pressure drop in the valve. Especially erosion caused by cavitation and solids is a consequence of the fluid velocity.

3.4.1.2 Cyclonic Principles in Petroleum Flow Regulations

A cyclonic valve is a potential low shear flow regulation valve [28]. The principle of a cyclonic valve is illustrated in figure 3-5 below.
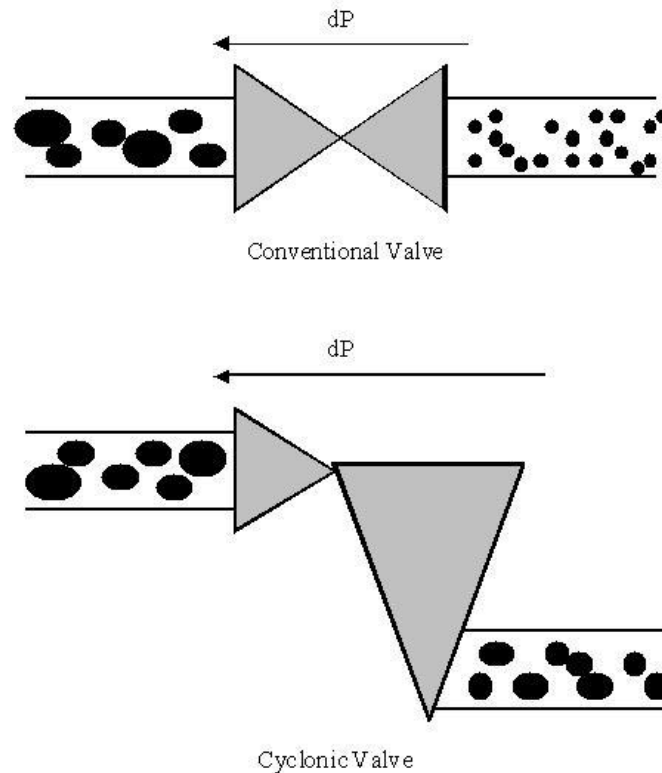
Figure 3-5: Effect of pressure drop on two-phase flow through a conventional and a cyclonic valve

Any valve will expose the fluid flow to an equal energy dissipation rate, *É,* (equation 3.1). Droplet break-up in a two phase flow through a restriction is proportional to the mean energy dissipation rate per unit mass, ε, (equation 3.3) This means, for a constant *É*, a reduction in ε will lead to reduced droplet break-up.

Flow regulation by cyclonic flow principles differ from conventional valve principles in two ways. At first, ε will be reduced. In a cyclone, most of the energy is dissipated within the regions where the turbulence and velocity gradients are largest, in other words, at the inlet and in the concentric area just outside the forced vortex. Also in cyclones, velocity gradients are present in the entire free vortex, especially in the region of the boundary layer adjacent to the cyclone wall. The second difference between a cyclone valve and a conventional valve is that centrifugal forces in the former enhance coalescence. Hence, the cyclonic principle in flow regulation will reduce droplet break-up and enhance coalescence, much like a hydrocyclone, and improve separation.

3.4.2   *State of the Art - Cyclonic Valves and Low Shear Technologies*
Enhanced separation of petroleum phases together with reduced fluid mixing and reduced emulsion viscosity has been very important for the oil industry in order to reduce negative environmental factors and better separation processes. The Typhoon valve is just one among many low shear valves that has been made in order to achieve this [28].

Fluid control by means of cyclonic principles is not a new thought. A 40-year old patent US3198214 [36], describes a through-flow fluid regulator which operates on cyclonic

principles. The outlet flow is here regulated by the speed of the tangential inlet flow. It is centrifugal forces of the vortex that determines the flow rate in the outlet(s), due to the location of the outlet(s) from the valve. The outlet(s) is located concentrically nearer the cyclone axis than the inlets.

Other valves based on cyclonic principles are power fluidic devices, also termed vortex valves. The vortex valves come in a variety of different configurations, but they all have in common that they use the strength/resistance of a spinning vortex to regulate or throttle the flow, nor are there any moving parts. Vortex valves have been known and used for decades, mainly in hydraulic, civil and nuclear engineering. There has also been developed a vortex choke valve, to combat the erosion problems in wellhead flow in petroleum production. The main flow goes through a radial inlet, into the cyclonic chamber and exits through an axial outlet. A second flow injected at the periphery of the cyclonic chamber regulates the rate of the main flow. Increasing the flow rate of the secondary flow regulates the flow rate of the main flow as this is restricted by the strength of the vortex. From the vortex chamber, the fluid exits through a diffuser-shaped outlet. To regulate the secondary flow, the cyclonic valve requires additional means, like pumps and valves.

The patent US5605172 [37] describes a cyclonic valve which has tangential inlets, like a conventional hydrocyclone. In this valve, a plug or a conical shape regulates the flow rate. The plug is guided into a cyclonic body where it gradually reduces the passageway of the swirling fluid. Another patent FR2588778 describes the same regulation principles. Here, a hydrocyclone for oil-water separation is equipped with flow regulation abilities. There are many other patents, like US2377721, DE19724056A1, GB1185274 and NO171300 [38, 39, 40] which describes the same principles in regulating the flow rate, and which are patented as cyclonic separators.

A patent in which the cyclone is a valve and function as a valve system and not a hydrocyclone separator is US2005173009 [41]. The principle is a cyclone which has two opposed tangential inlets. These inlets enables a flow rate regulation by establishing vortex strength, hence a fluid pressure drop over the cyclone.

Besides the vortex choke valve, there are no other publications which describes the cyclonic valve principle for petroleum applications. Two of the patents recently described above, GB1185274 and US5605172, as well as GB2239191 [42] are cyclonic valves developed to coalesce dispersed phases, which ease the downstream separation. They are target especially for the petroleum industry and processing.

3.4.2.1 *Choke modification done by Delft University*
Experimental work has been carried out by Delft University of Technology in the Netherlands with focus on modified choke design, reduced oil droplet break-up under high water-cut production wells [34]. High energy dissipation in the choke due to pressure drop within the system leads to severe break-up of dispersed oil droplets. Previous experimental work has found that break-up is a result of the choke geometry, and modifications on the geometry may reduce droplet break-up. Results from the experimental work showed that it was possible to reduce droplet break-up by modification on the choke and with the use of parallel tubes.

Because energy dissipation rate in the choke is inverse proportional to the length, the bigger/longer the choke is, the less turbulence in the choke, hence droplet break-up.

Three model chokes were tested, an orifice, a small choke consisting of 7 parallel tubes and a larger choke consisting of 13 parallel tubes. These three chokes were tested with the same test parameters, the same flow rate and the same pressure drop across the chokes. The results were that the largest choke was superior, less droplet break-up occurred in this device. Some droplet break-up occurred in the small model choke, while severe break-up occurred in the circular orifice.

3.4.2.2   *Cyclonic low shear valve testing done by Petrobras in Brazil*
Petrobras has tested a cyclonic low shear valve prototype at Petrobras Experimental Center (NUEX) in Aracaju/SE [35]. The valve can be used as a choke valve, as a valve between separation stages and for controlling the level of vessels.

The cyclonic low shear valve is a modified conventional globe valve, and the modified cyclonic valve has been tested and compared with a conventional globe valve. The purpose of the testing was to demonstrate the advantages of using a low shear cyclonic valve instead of a conventional valve in separation processes. The results from the tests showed that the cyclonic valve had a better performance compared with the conventional valve, and that the performance was a function of several parameters, like emulsion stability, water content free, and oil properties

3.4.2.3   *Separation system comprising a swirl valve*
Twister (US2012/0090467 A1) [31] has invented a low shear separation system which comprises of a swirl valve which receives and controls the flux of a fluid flow via the flow inlet and generates a swirling flow. A separation chamber downstream the swirl valve receives the swirling flow, and comprises a first and second flow outlet. The first flow outlet receives an inner portion of the swirling flow, while the second flow outlet receives an outer portion of the swirling flow. The swirling flow has two advantages:

1) Regular velocity pattern which leads to less interfacial shear, less droplet break-up and larger droplets.
2) The concentration of droplets in the circumference of the flow area increases which means large number density, improved coalescence and larger droplets.

The swirl valve has a cage with tangential openings instead of radial openings which conventional valves have. The tangential openings makes a more regular swirl pattern, this introduces less shear forces and less droplet break-up and more coalescence than with conventional valves. Radial openings introduces higher shear forces, hence droplets break-up into smaller droplets.

3.4.2.4 *Kouba patent by Chevron*

Chevron has taken patent on the Kouba technology (6730236 B2) [32]. The invention is a mechanical flow conditioning technology for improving downstream separation of oil, water and gas, and swirling the bulk flow to enhance coalescence of the dispersed phase. Most conventional separation systems and pipelines tend to shear and disperse coalesced droplets and stratified layers of fluid components when the fluid is passed through the flow control apparatus. Conventional flow control apparatus are typically designed such that there is a rapid change in both the flow rate and direction of a fluid mixture passing through the flow control, and energy is dissipated into the fluid. As the rate of energy dissipation increases, break-up of coalesced droplets occur and smaller droplets are created. The concept behind this patent includes reduction of forces that are responsible for droplet break-up as well as enhancing coalescence of the dispersed phase.

3.5 Total Valve

Total, with Stephane Jouenne has invented a flow control valve specially adapted for polymer solutions (WO2012001671) [43]. The invention consists of both a method for transportation of the solution, as well as a method for injecting the solution into a subterranean formation, using a flow control valve. The present invention is illustrated in figure 3-6 below.
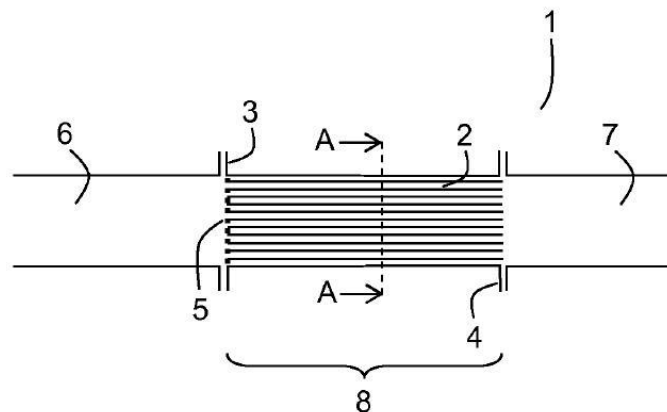
Figure 3-6: Flow control valve with integrated injection pipe

The present invention contains an injection pipe comprising a single tube, and a flow control valve comprises at least 10 tubes, preferably 100 tubes which are arranged in parallel. The ratio of the section of the single tube of the main part on the sum of the sections of the tubes conveying fluid from the flow control valve is less than or equal to 5, preferably less than or equal to 1.5. The fluid from the injection pipe is then injected into a subterranean formation.

With reference to figure 3-6 above, the embodiment contains a conveyor line, including a injection line, a major portion (6) having a single tube and a flow control valve (8) which is connected to the injection line by means of connection (3). The other side of the main portion is connected to the fluid supply, this is not shown. The fluid supply is most often a fluid reservoir and a pump. A plurality of injection line is often connected to one fluid reservoir, and the pump is adapted to circulate the fluid pressure in the main portion of each duct, and then through the flow control valve. The fluid is in this case a polymer solution, most often a

polyacrylamide, which preferably have a molecular weight greater than 10^6 Da (1 Da = 1 g/mol), but other fluids which are susceptible to mechanical damage can also be used. Examples are emulsions, like oil/water emulsions.

According to the embodiment, the flow control valve is connected to a second main part (7) via a connector (4), and which comprises a single tube. The fluid flows in through the main portion (6), then through the control valve (8) and then into the second main part (7) before the fluid is injected into a subterranean formation.

The flow control valve (8) contains a plurality of fluid transport tubes (2) arranged in parallel in the direction of flow. The term "parallel" in this case, means that the fluid transport tubes are arranged such that the fluid from the main portion (6) partitions into every fluid transport tubes (2). The sum of the individual capacities of fluid in the various fluid transport tubes equals the total flow of fluid in the main portion. The number of transport tubes should be higher than 10, more preferably higher than 5000. The more fluid transport tubes, the higher pressure drop can be generated with minimal mechanical degradation. Figure 3-7 below illustrates the transport tubes.
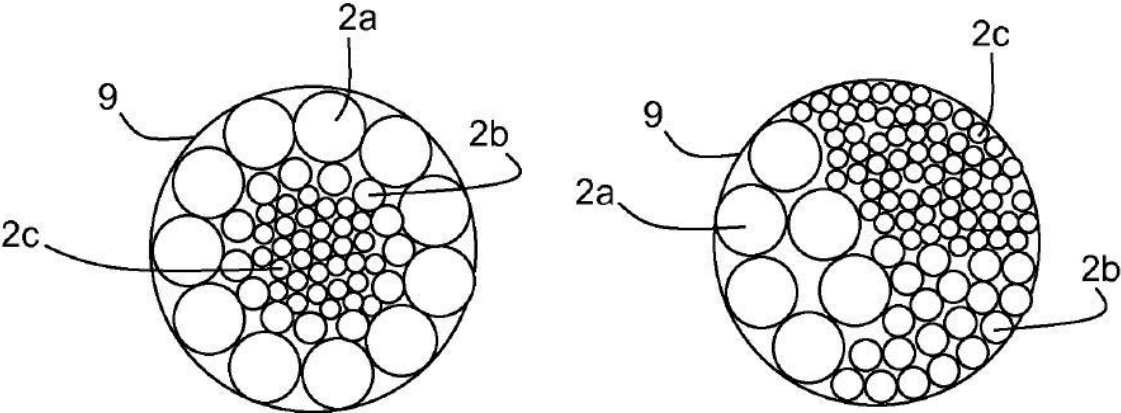
Figure 3-7: Illustration of the arrangement of transport tubes in the present invention

The transport tubes are arranged into a beam which can be contained in a sheet (9). Preferably, the sheet is cylindrical with a circular base, but it may take other forms. It is also preferably that the fluid transport tubes have a cylindrical cross section, but the cross section may also take other forms.

The portion of the fluid transport tubes must have a section at least 10 times smaller than the section of the single tube of the main portion, preferably at least 10000 times smaller. The use of many fluid transport tubes with small sections compared to the cross section of the main tube portion, creates a high pressure drop with minimal mechanical degradation, for a given flow rate.

The flow control valve may be free for sealing. This means that the fluid flows in the entire fluid transport pipe. However, it is preferable to provide closing (5) of the conveying fluid transport tubes. These closings are arranges at the inlet of the fluid transport pipes (at the

interface between the main portion of the pipe, and the fluid transport tubes), or alternatively, at the output of the fluid transport pipes (at the interface between the second main portion of the pipe and the fluid transport tubes). The sealing should contain a single moving part or a set of movable parts cooperating with each other (for example a piston), in addition to non-movable parts which are operated independently of each other.

The fluid transport tubes should have identical shapes. However, it is preferred that the sections are not all identical. It is useful to provide some fluid transport tubes with relatively large sections, in addition to some fluid transport tubes with relatively small sections. By passing the fluid through the fluid transport tubes with large sections, the pressure drop for a given flow is reduced. And by passing the fluid through the fluid transport tubes with small sections, the pressure drop for a given flow is increased. This is done by selective blocking of either the fluid transport tubes with large sections, or the fluid transport tubes with small sections, allowing the fluid to be transported into the tubes that are not blocked. Figure 3-7 above illustrates the use of fluid transport tubes with different sections. The length of the fluid transport tubes should be the same length for simplicity. A length of 1-10 m is preferred, but more preferably from 30 cm – 1.5 m. The inventor of the present invention found that degradation of the polymer solution occurred substantially only at the inlet of the fluid transport tubes, and not on the whole length. Therefore, by making the tubes longer, a large pressure drop for a given flow rate can be provided, without generating significant degradation. The results of the testing with capillary length is to be found in figure 3-10 below, which indicates that the degradation of polymer only occurs at the inlet of the capillary tube.

It is advantageous that the contraction ratio, that is, the ratio of the section of the single tube of the main portion of the sum of the fluid transport pipes, is greater than 1 and preferably less than 3. This is to provide the section of the sheet which is not available for passage as small as possible, to limit local contraction ratios, and limit the degradation of the fluid.

The geometric characteristics of the flow control valve, namely the size, number and length of the fluid transport pipes are selected as a function of the flow rate range and the pressure drop range which is desired.

Tests were done to confirm that the present invention did decrease the mechanical degradation of polymer. A polyacrylamide solution of 800 ppm was used, with capillary tubes of 0.18 mm, 0.25 mm, 0.5 mm and 0.75 mm, and with a length of 30 cm. The pressure drop range was from 0 – 20 bars, and the flow rate was 0 – 400 cc/min, depending on the diameter of the capillary tube.

Figure 3-8 and 3-9 below illustrates that the mechanical degradation of polymer decreases when the diameter of the capillary decreases and when the length of the capillary tubes increases.
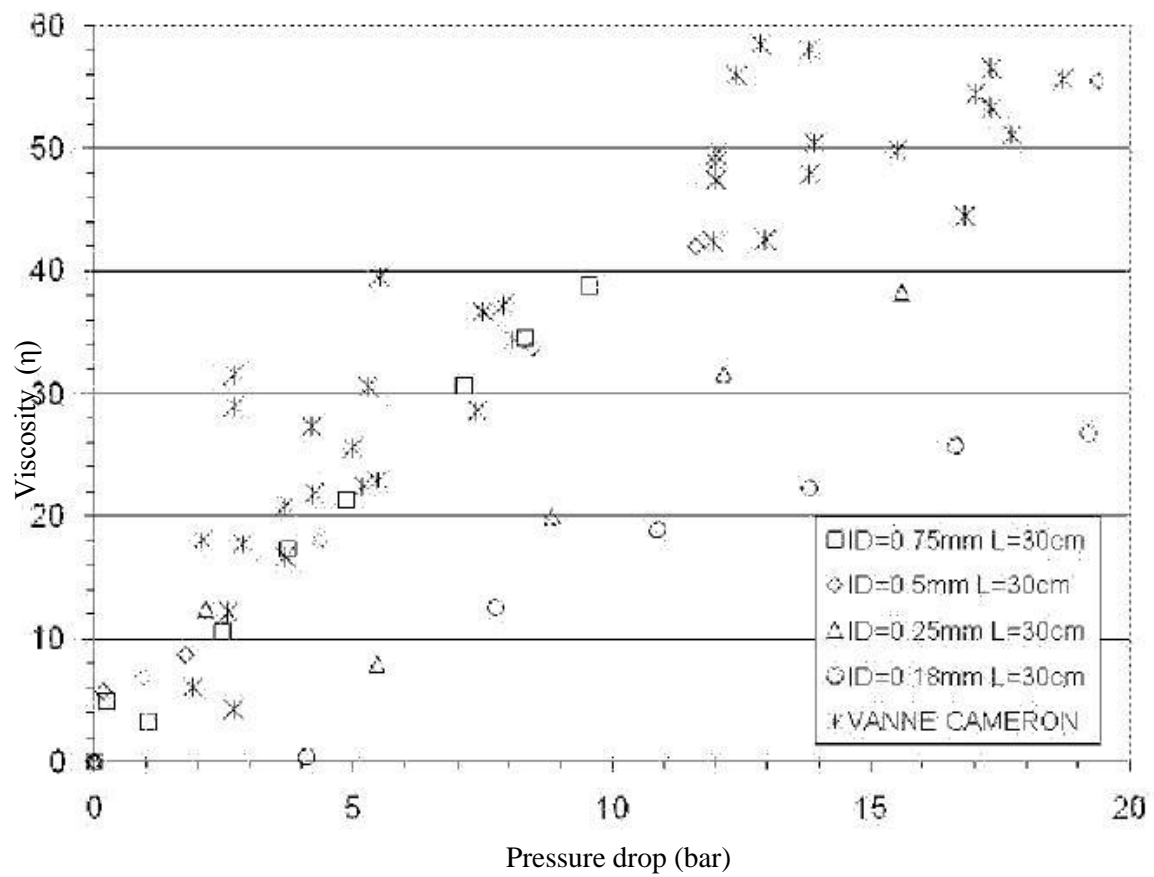
Figure 3-8: Degradation of the polymer with decreasing diameter of the capillary tube
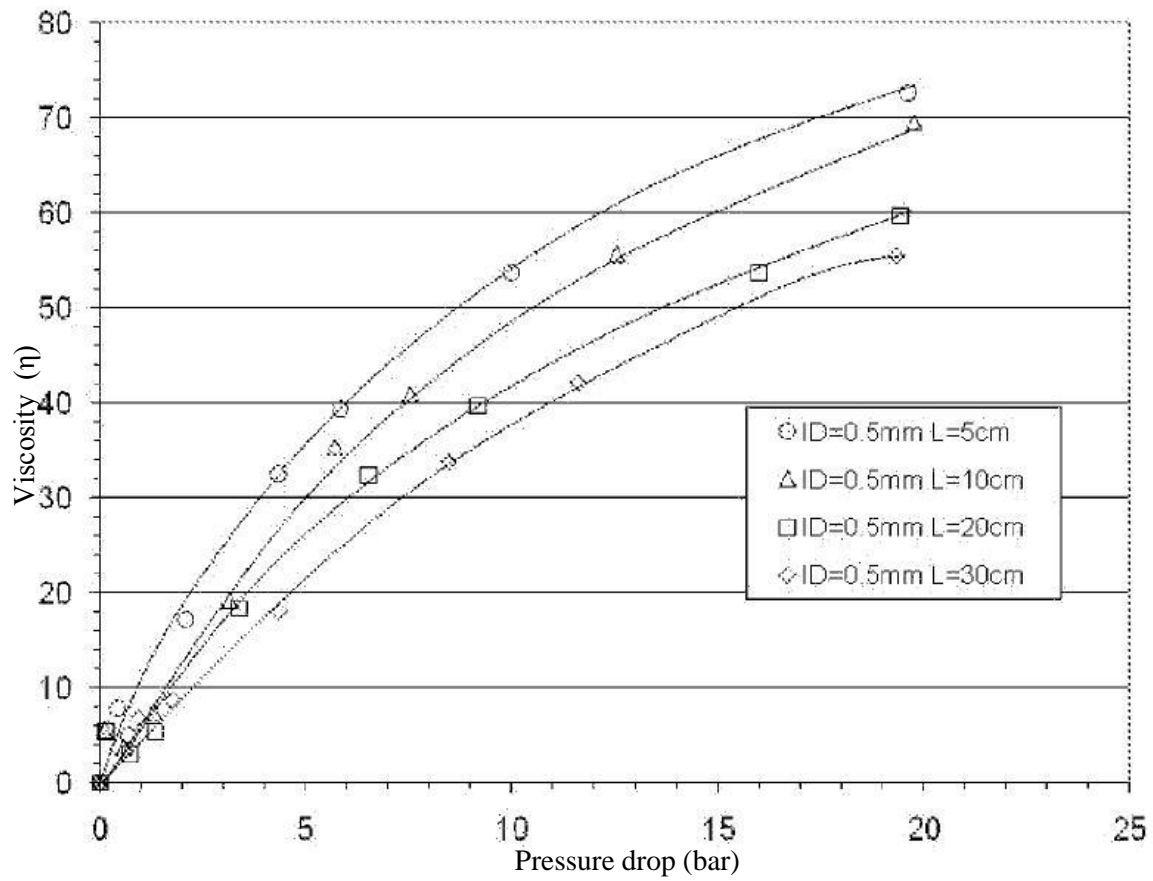
Figure 3-9: Degradation of the polymer with increasing length of the capillary tube

Results from the tests that confirmed that the degradation of the polymer only occurred at the inlet of the flow transport tubes are illustrated in figure 3-10 below.
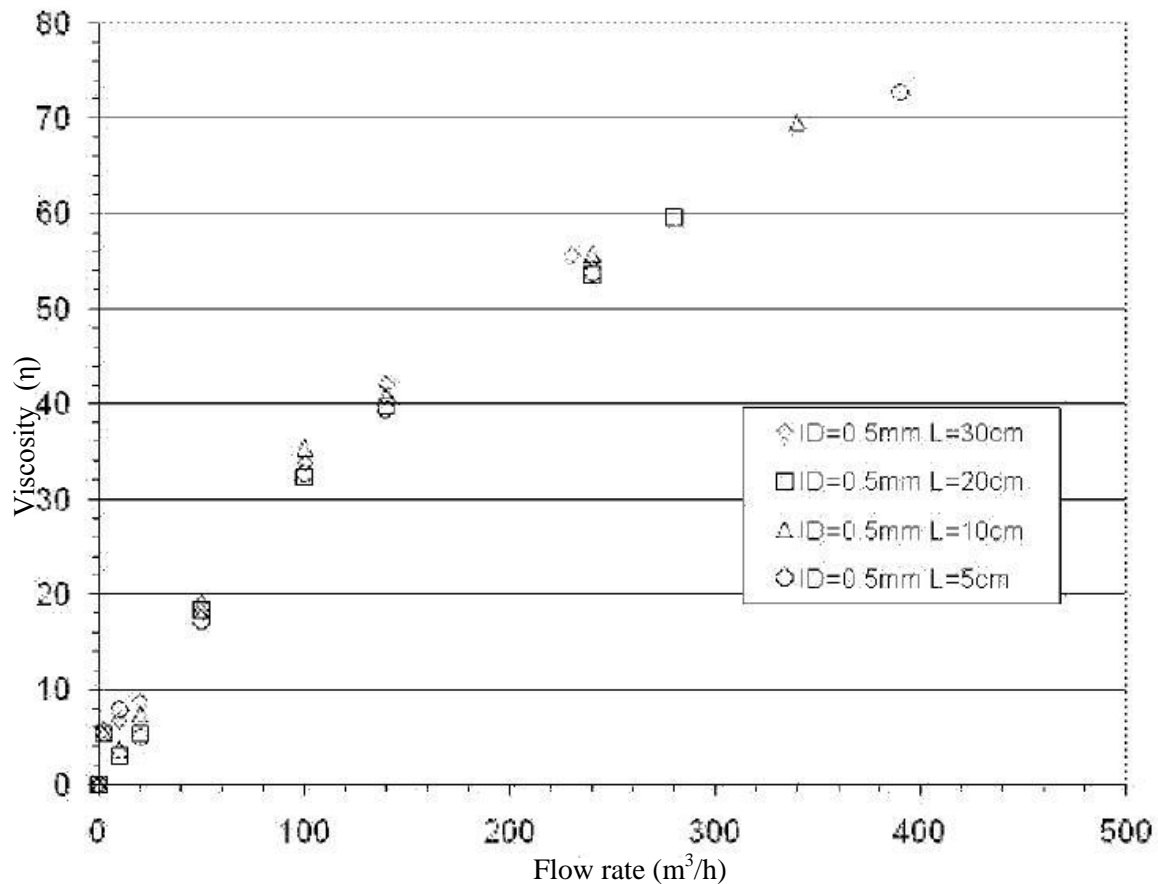
Figure 3-10: Degradation of the polymer and the capillary tube inlet

The present invention can be implemented on shore or offshore. The use of this invention is not limited to the field of enhanced oil recovery; it can also be used in all other technical areas which require transport of pressurized fluid, especially pressurized fluid sensitive to mechanical degradation.

There are many variants of this invention, where the tubes are divided different, and other where the main axis of the flow control valve is different.

3.6 Background for Total Valve

Total's flow control valve for minimized degradation of polymers used in enhanced oil recovery (EOR) is not the first. There are many other valves which support polymer flooding, but they often have disadvantages. Willis Cameron is one company that has proposed a control valve and a model for this application. The model consists of a cage with holes, and the entry of the fluid occurs at the periphery of the cage, and the outlet is the center of the cage. A movable piston is parallel to the cage axis, which function is to adjust the accessible surface area available for the fluid. As the available surface area decreases, the pressure loss increases for a given flow rate, and the result is severe degradation of the polymer used, hence the effectiveness is reduced.

There are also other valve patents which function is to reduce polymer degradation in EOR. Some of them are briefly mentioned in the chapters below, and is a part of the background for the Total valve. For a full review of each patent, see chapter A.3 in Appendix A.

3.6.1 *Flow control apparatus and method*

A flow control valve which purpose is to control the flow of dilute polymer solutions without causing any significant degradation of the polymer has been invented by Luetzelschwab (US4510993) [44]. The invention comprises both an apparatus and a method which enables transport of dilute polymers with substantially no degradation. The apparatus consist of a needle valve positioned in a conduit for transport in one embodiment, and a self-adjusting flow regulator in another embodiment. The self-adjusting flow regulator contains a tapered throttle on a reciprocatable piston. The result is the need of smaller volume of polymer solution in addition to enhanced oil recovery.

3.6.2 *Adjustable pressure reducing valve*

The pressure on a flowing liquid, such as a polymer solution, can be reduced by the use of a packing of displaceable solid shapes such as sand or beads, in the conduit, such that the pressure drop, hence the degradation of the polymer is decreased. Seawood Seawell has patented a valve (US3477467) which compromises packing of displaceable solid shapes within at least a plurality of conduits interconnected in a parallel flow pattern [45]. Shut-off valves at the inlets of the conduits may displace the solid shapes into conduits called storage legs. By adjusting the length of the packing of the solid shapes, the pressure drop can be controlled. This subjects the solution to minimal shear force, thus minimal degradation.

3.6.3 *Polymer flow control apparatus*

Luetzelschwab has a patent on a positive-displacement flow device (US4617991) [46]. The invention is an apparatus which controls the flow of aqueous partially hydrolyzed polymer solution to minimize degradation of the polymer. The present invention utilizes a positive displacement device positioned along the flow path. The device can be flow meters, pumps, like piston pumps or vane pumps, and hydraulic motors such as piston motors or gear motors. By varying the rate at which energy is removed from the polymer stream, flow rate is obtained. The forms that remove energy may differ, but in one form the rotational work imparted on the fluid may be translated. One example of such a system is the use of a hydraulic pump which motor is coupled to an air compressor. By varying the discharge pressure of the compressor by a valve, the extraction of energy from the polymer stream can be controlled, thus the rate of flow across the motor.

3.6.4 *Adjustable flow rate controller for polymer solutions*

Another conventional method for controlling the flow of polymer into the wellhead with minimum degradation is the use of "choke coils". Jackson has invented a coil which will give maximum 25% degradation of the polymer solution when it is injected into the well heads (US4276904), in addition to controlling the flow of polymer solutions [33]. These coils give less degradation of the polymer, however, the shortcoming of the coils are that there is no

adjustment to simply and quickly alter the pressure drop provided by the device. If it is necessary to change the amount of restriction of flow, the operator has to disconnect the coil from the injection line, and shorten or lengthen the coils in the device.

The invention done by Jackson is a device which can vary the flow rate of shear degradable polymer solutions which will not cause an undesirable degradation of the polymer solution.

3.7   Typhonix's Flow Control Device (Shark)

In the petroleum production and processing, mechanical devices such as choke and control valves are normally used to alter and control the flow rate and pressure, known as flow control. Choke valves are often used on well heads to reduce the pressure of the well stream, in addition to control the rate of production. Control valves are normally associated with separators. They regulate the levels of fluids in different separators, and control the fluid flow in-between them. The need for choke and control valves are obvious to maintain flow control, and to accommodate the desired process requirements, however there are many unwanted effects associated with both choke and control valves. The unwanted effects may be severe for the integrity of the valve, as well as the system which surrounds them, and the effects are [47]:

1. Fluid mixing
2. Particle erosion in valve
3. Cavitation erosion in valve
4. Noise from valve
5. Valve vibration

1. Fluid mixing
A fluid flow will normally undergo substantially mixing when subjected to a flow device such as a choke or control valve. The mixing will not have influence on the valve itself, but the efficiency of the downstream process system will be greatly affected. Downstream separation of oil, gas and water in the petroleum industry will due to large turbulence and shear forces in the choke and control valves be deteriorated, thus the quality of the separated fluids will be degraded.

2. Particle erosion in valve
In petroleum applications, erosion in valves is a major problem. The fluid in the production well is often associated with sand and particles. When the velocity of the fluid is raised, and the particles impact on the valve internals, erosion may occur. It is usually the flow regulation part, the trim that gets eroded, thus the valve looses its main function of flow control. Erosion is a function of particle speed and impact angle. A solution to erosion is thus to reduce particle speed, hence the impact angle. The pressure drop can be created across several stages rather than just one stage. Erosion resistant materials and mechanical and geometrical valve solutions have also been used to minimize erosion.

3. Cavitation erosion in valve

Cavitation, as with particles, has also a strong eroding effect. With the use of multistage trim solutions, the erosion caused by cavitation may be reduced.

4. Noise and vibration

High fluid velocities and fluctuations in fluid velocities often results in noise and vibration. Especially with small volumes, the noise and vibration levels are high, due to high fluid velocities and turbulence.

3.7.1 The present invention

The invention is a spiral shaped flow device for creation of pressure drop and flow control. The length, shape and cross sectional flow area of the spiral, and the number of spirals can be adjusted to achieve the desired turbulence and pressure drop for a given fluid flow. All the unwanted valve effects mentioned above can be reduced with the spiral.

The invention is a throttle valve or flow control device for fluid control, or pressure regulation in single or multiphase flow applications associated with fluid shearing, erosion, cavitation and noise. The invention comprises a spiral shaped fluid channel or channels, which purpose is to create continuous frictional pressure drop along the flow axis, in addition to measurers to open or shut off the flow channel, or channels. The device may be arranged like spirals or coils on a disc or cone, or on a plurality of discs or cones, forming a disk-stack or cone-stack. The disk-stack or cone-stack can contribute to restriction of flow, or be equipped with a regulation mechanism which restricts the flow or completely blocks off the flow. This regulation mechanism may be a circular plug which moves in a circular center hole of the disk-stack, and which fully open or block off the openings of the disks. Different types of spirals are illustrated in figure 3-11 below.
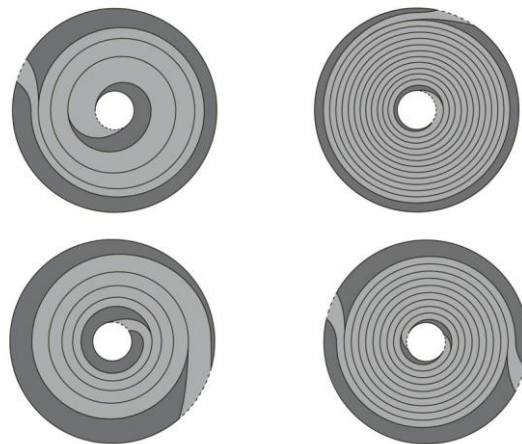
Figure 3-11: Different types of spirals of the present invention

The spirals to the left in figure 3-11 have a shorter length, and a bigger diameter which results in less pressure drop. The spirals to the right have longer length, but smaller diameter, which causes an increased pressure drop.

The areas of application for the present invention are:

1. Adjustable throttling device, either as a choke or control valve
2. Fixed throttling device
3. Coalescer in produced water processes
4. Coalescer in oil processes

1. Adjustable throttling device
As mentioned above, with the use of choke and control valves, the fluid stream mix the petroleum phases, such that the efficiency of the downstream separators is reduced. Oil droplets may be dispersed in the water phase, water droplets dispersed in the oil phase, or that gas is mixed into the liquid. The efficiency of the separation of the fluid phases is reduced, and the quality of the end product is degraded. The principle behind the invented spiral/coil flow device will improve separation of oil, thus the quality of the end product will be improved compared to the result with conventional choke or control valves. The following examples illustrate where the invented device may be used, and how it can enhance the separation.

The invented device can be used as a choke valve on a well head. The phase components will be less mixed together due to the act of reducing the pressure of the flow. The fluid exiting the choke valve will contain phases that will easier separate in a separator.

The invention, if used as a control valve on a 1st stage separator oil outlet, will to a less degree break the water droplets remaining in the oil phase into smaller droplets. The efficiency of the downstream separator will thus be increased, which function is to remove the remaining water droplets from the oil phase, and the quality of the oil product is improved.

The invention, if used as a control valve on a 1st stage separator gas outlet, will to a less degree break the liquid droplets remaining in the gas phase into smaller droplets. The efficiency of the downstream separator will thus be increased, which function is to remove the remaining liquid droplets from the gas phase, and the quality of the gas product is improved.

The present invention may also benefit as an injection choke valve and a low shear flow control valve. This is especially relevant with regard to water injection processes and polymer injection to increase the recovery rate of a petroleum reservoir. As noted, polymers undergo severe degradation when subjected to high shear, but the present invention may prevent the degradation due to less pressure drop, hence less turbulence. The result will be increases efficiency of the injection process, and higher oil recovery from the reservoir.

2. Coalescer in produced water processes
There are strict regulations for discharge of produced water to sea, and injection of produced water into the reservoir. Produced water has to be treated to remove the remaining oil before it can be discharges or re-injected. This is normally done in a produced water treatment plant, which is a part of hydrocarbon process plant. Often, at first, the produced water is separated in large gravity separators, which due to gravity and differences in density, separates the water and oil phase from each other. However, the separated water, which is the effluent, normally

contains some droplets of oil, and other processes have to be used to remove the remaining oil droplets. The processes which are used to remove the remaining oil droplets may be de-oiling processes in a hydrocyclone, plate separators, gas-flotation units etc. The efficiency of the separators is a function of oil droplet size, and the relationship between oil droplet size and settling velocity is described by Stokes' law (equation 3.5) [48].

$$v_S = \frac{g \ P_p - P_m \ D_{p^2}}{18 \ \mu} \hspace{3cm} (3.5)$$

Where:
V_s = Settling velocity
g = Gravity
P_p = Density of particle
P_m = Density of medium
$D_p{}^2$ = Particle diameter
μ = Viscosity

If the oil droplets are too small, e.g. a few micrometers, the efficiency of the oil-water separation may be poor. The bigger the droplets, the faster it settles, in accordance with Stokes' law. To overcome this problem, chemicals like coagulants and flocculants may be used, which enhances the coagulation process of oil droplets. In other cases, static coalescer is used, which due to metal or oleophilic materials attracts oil droplets, and enlarges them.

The present invention may be used as a coalescer, and will enhance the coalescence of droplets of a dispersed phase in a continuous phase. It is the turbulence which is created in a defined volume, and constant pressure drop which aid coalescence of droplets of a dispersed phase in a continuous phase. The result is droplet enlargement, and this will have a positive effect on the downstream separation systems, where separation efficiency is proportional with droplet size. The downstream systems may be produced water treatment systems, such as hydrocyclones, gravity separators, or centrifuges which separates oil from the water phase. Conventional valves will normally, due to excessive shearing and turbulence, break up the droplets rather then enlarging them, hence have a negative effect on the downstream separation efficiency. The present invention can reduce the droplet break up, due to controlled and reduced turbulence, which will enhance coalescence of droplets rather then breaking them. When the pressure reduction required by the valve is very high, the present invention can be placed upstream the separator, and achieve droplet enlargement.

The degree of coalescence of oil droplets can be adjusted by the turbulence created through the spiral conduit, and the residence time. The turbulence is adjusted by altering the pressures across the device and the control valve. The total pressure drop is maintained but the pressures are shifted from one device to another. If less pressure is needed across the device, the pressure is shifted from the device to the control valve. This is achieved by closing the

control valve, and opening the device. Oil droplet analysis should be conducted to achieve optimal pressure/turbulence conditions.

3.7.2 Different configurations

Depending on field conditions, and practical requirements, the present invention can be used in many different configurations, which are all described in the sections below.

1. Single conduit spiral with constant cross sectional flow area arranged on a supporting structure
2. Dual or multiple conduit spiral with constant cross sectional flow area arranged on a supporting structure
3. Single conduit spiral with increasing cross sectional flow area arranged on a flat or coned disc
4. Single conduit spiral with constant cross sectional flow area not arranged on a supporting structure
5. Single conduit spiral with constant cross sectional flow area not arranged on a supporting structure

1. Single conduit spiral with constant cross sectional flow area arranged on a supporting structure

With this configuration, the spiral has an inlet in one end, and an outlet in the other end. The fluid enters the inlet, and flows through the spiraled conduit, and out the spiral outlet. The conduit may have any form, like circular, rectangular, elliptical etc. The shape of the conduit should preferably have a shape that let the flow through easily, even particles which may be in the flowing stream. The supporting structure may be coned or flat, and makes up the wall of the spiral. If a flat disc is used, on one turn (360 degrees), the spiral diameter increases proportionally with the diameter of the spiral conduit. If a coned disc is used, on one turn (360 degrees), the spiral diameter increases as a function of both the spiral conduit diameter and the cone angle. By coning the disk, the maximum disc diameter is reduced.

The inlet and outlet may be arranged differently. The inlet may be near the inlet centre, and the outlet may be at the periphery, or vice versa. When the inlet is near the centre, the spiral diameter increases towards the outlet. If the inlet is at the periphery the spiral diameter decreases towards the outlet. In both the alternatives, the purpose of the spiral flow is to expose the fluid to a continuous pressure drop along the fluid flow axis, such that the fluid flow has created a constant pressure drop from inlet to outlet.

A radial fixed conduit cross section increases the disc diameter, which increases the spiral length. An increase in the spiral length will increase the pressure drop for a given flow rate, or reduces the flow rate for a given pressure drop. In other words, the disc diameter which is a design parameter, which can be altered to match a desired capacity, pressure drop and flow rate.

The spiral conduit radial cross section and the cross sectional flow area is another design parameter. With a fixed disc diameter, an increase in the radial cross section will give a shorter spiral with an increased cross sectional flow area. This reduces the pressure drop for a given flow rate, or increases the flow rate for a given pressure drop. An increase in the conduits cross section will in other words increase the capacity.

With a fixed disc diameter, and when the conduit's radial cross section and the cross sectional area is reduced, the spiral length is increased. This increases the fluid pressure drop for a given flow rate, or reduces the flow rate for a given pressure drop. An increase in the disc diameter at a fixed pressure drop and flow rate will increase the spiral flow volume, and the volume is involved in creating the pressure drop.

2. Dual or multiple conduit spirals with constant cross sectional flow area arranged on a supporting structure
This configuration is the same as in 1, but instead of one conduit spiral, there are two or more conduit spirals. The inlets are preferably spaced equally around the circumference, depending on the flow direction, either at the periphery or near the centre of the wall. An increase in the number of spiral conduits reduces the axial flow length of each spiral, for a given conduit cross section and supporting structure diameter.

3. Single conduit spiral with increasing cross sectional flow area arranged on a flat or coned disc
The increase in cross sectional area in the flow direction offset an increase in flow velocity due to expansion on pressure reduction downwards the spiral, or due to gas release.

In this configuration, the single conduit spiral is arranged with one inlet and one outlet. The inlet may be near the centre of the disk or at the periphery at the disk, and the outlet at the periphery of the disk or at the centre of the disk respectively. In these alternatives, the spiral flow exposes the fluid to continuous pressure drop along the fluid flow axis. This gives the flow from the spiral inlet to the outlet a wanted permanent pressure drop to the fluid.

4. Single conduit spiral with increasing cross sectional flow area not arranged on a supporting structure
In this configuration, the spiral conduit is tubular arrangement, just like a pipe being coiled up to from the shape of a spiral. The cross sectional area may be of any shape like circular, squared, rectangular, elliptical etc. The coiled up pipe may be arranged in one plane or as a cone. When the pipe is arranged in one plane, the spiral diameter on each turn (360 degrees) increases at least proportionally to the pipe diameter. The spiral diameter on each turn (360 degrees) increases as a function of the spiral conduit diameter and the cone angle when the pipe is arranged such that the spiral makes up a cone. Coning the pipe reduces the maximum diameter.

5. Single conduit spiral with constant cross sectional flow area not arranged on a supporting structure

In this configuration, the pipe spiral is arranged with constant diameter and the coil makes up the shape of a cylinder. The cylinder length is a function of the spiral length and the distance between each coil turn in the cylinder axis direction. A larger diameter of the spiral conduit reduces the pressure drop for a fixed flow distance.

Depending on the application, the invention may be arranged in different ways. Other method arrangements may be to use the spiral/coil disk-stack arrangement in a choke or control valve.

3.8 Background for Typhonix's Flow Control Device (Shark)

There are other patens which uses spirals for separation of oil and water. Some of the patens which are background for the Shark are briefly described in the sections below, for a full review of each patent, see chapter A.4 in Appendix A.

3.8.1 Spiral mixer for floc conditioning

This invention by Lean et al., (US2010/0314325 A1) is a system and method for treatment of water containing particles [49]. The device contains an inlet which receives the source water, a spiral mixer, buffer tank, spiral separator and an outlet having two paths, one path for the effluent, and one path for the waste water containing the aggregated floc particles. The spiral mixer mixes the source water with a coagulant material and an alkalinity material, and performs in-line coagulation and flocculation processes within the spiral channels. The buffer tank receives the aggregates from the mixer, and allows them to grow beyond the cut-off size of the spiral separator. The separator separates the content from the buffer tank into affluent and waste water with aggregated floc particles. The invention uses spirals with channels which are custom designed to achieve a shear rate which enhances the growth of floc particles with a narrow and uniform size range.

This invention benefit over the traditional water treatment plants in high scalability, modularity, small footprint, high throughput, purely fluidic, continuous flow, membrane-less, size selective cut-off and accelerated agglomeration kinetics. The system will work with particulates of any density, but especially those with neutral buoyancy. The result of all of these features is reduced coagulant dosage, up to 50% reduction in coagulant dosage to achieve the same turbidity reduction as with traditional treatment plants.

3.8.2 Platform technology for industrial separations

This invention by Lean et al., (US2010/0314328 A1) is a system for treatment of a fluid stream with a spiral mixer [50]. The fluid flow is received by a spiral mixer which mixes and conditions the input stream. The mixed fluid stream is then input to a spiral separator which separates the fluid stream into at least two fluid streams. One stream having removed all the particulates, while the other stream has the particulates in the stream concentrated.

Aggregation of particles by the spiral mixer-conditioner can be achieved in two ways. By changing the geometry of the cross section of the spiral mixer or by change the flow rate speed, the shear rate, hence the aggregation of particles can be controlled. The size of the

aggregate leaving the mixer can be related to the shear rate, which is the gradient of the transverse velocity. As the shear rate increases, the size of the aggregates decreases. By increasing the flow rate velocity within the channels, the shear rate increases, and particles tend to break up in smaller aggregates. By controlling the flow rate, the shear rate can be designed and controlled. The result is dense uniformly-sized aggregates which are efficient separated by a downstream spiral separator.

3.9 BACHELOR THESIS – TESTING OF COIL

Vladimir Marchenkov (bachelor thesis, 2012) [51] has done previous testing of the coils which is described in chapter 3.8. It is his study that led to the assumption that these coils may have a positive influence on mechanical degradation of polymers. The following chapters describe his thesis, and all the information is taken from his study and work.

The test objective in this bachelor thesis was to study dispersion phenomenon in flow of oil and water through pipes and restrictions, which can be correlated to the project objective in this thesis. His study and droplet break-up and coalescence in coils can be directly compared with the degradation study of polymer solutions in the same coils, this is why a short review on his thesis is described in this chapter. For a full review, together with the theory behind the thesis, see chapter A.5 in Appendix A.

His study took place in Typhonix's own laboratory, where a specific characterization rig was built, and different concentrations of oil-in-water emulsions with Kobbe and Grane crudes were used. The effect of different restriction sizes and lengths on droplet break-up and coalescence were studied. The different tests were carried out with 1" straight pipe together with spiral shaped pipe sections of 6mm, 8 mm, 10mm, 12mm, and 15mm and 1", and at different flow rates. Laser diffraction measured the droplet-size distribution.

To briefly summarize, the results varied based on coil size and mixing conditions. However, it was concluded, based on the results, that these coils are beneficial, and have a positive effect on oil droplet size, with regard to coalescence and droplet break-up. All the results with discussion are to find in appendix A, chapter A.5..

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4 *METHODOLOGIES*

This chapter is divided into two main chapters. One comprising the testing of the Typhoon Valve in France (chapter 4.1), which was part of the pre-project, the other chapter comprises testing of cones and coils (Shark), a Standard valve and a Typhoon Valve configuration, here in Typhonix's own laboratory (chapter 4.2), as a part of the ongoing main project. Both projects are joint industry projects between Typhonix, Total (PERL) in Lacq, IRIS and The Research Council in Norway. Total have a own division in Lacq with expertise and research in polymer injection, while IRIS has a research facility in Stavanger, with expertise in polymer injection and shear degradation.

The chapters describes the methodology used to study the effect the Typhoon valve and the fluid flow apparatus have on degradation of polymer compared to the state of art technology.

4.1 *Testing of Typhoon Valve – Pre-Project*

The main project objective in the joint pre-project was to find a low shear injection method for polymers, with the use of low shear valves and pumps (Typhoon Valve and Pump). For a full review over the project objectives, see chapter A.1 in appendix A.

A polymer injection 2" test loop has been build at Total's facilities in Lacq to test and study the mechanical degradation of polymer due to shear stress in Typhoon Valve, compared to conventional valves. This chapter provides the functionality and features of the test loop, as well as the test program, and the methods used.

4.1.1 *Test-rig functionality*

To study mechanical degradation of polymer solutions in the Typhoon Valve, a 2" test-rig was used at Total's facilities for polymer research, in Lacq. An illustration of the test-rig is shown in figure 4-1 below [52].
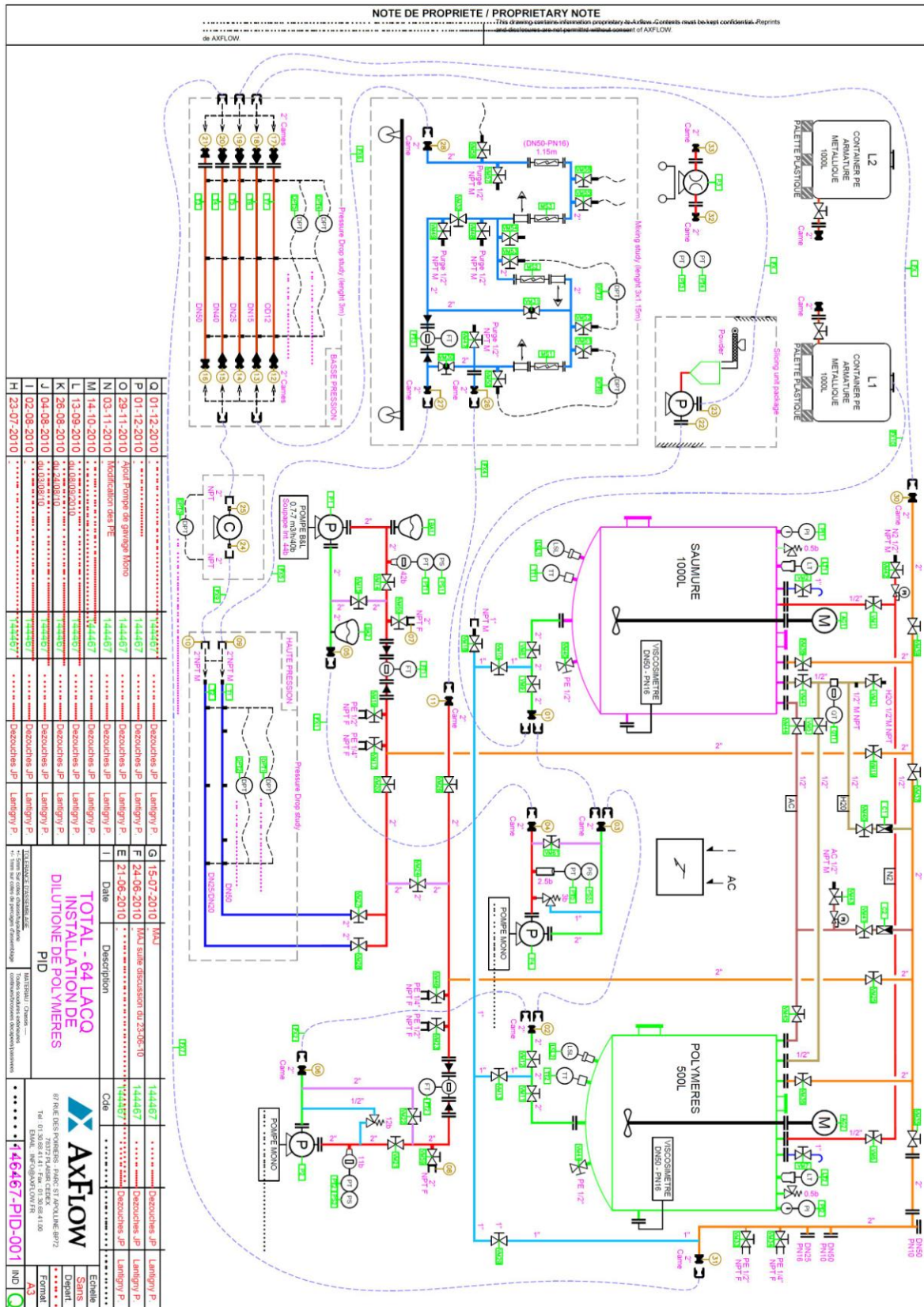
Figure 4-1: Illustration of the polymer test-rig used in Lacq

Synthetic sea water (29000 mg/l) with added polymer solution (800 ppm) was tested in the test loop. The test-rig contained two tanks with polymer solution. One tank held the mother

solution (undiluted), while the other tank held the diluted polymer solution (800 ppm). From the tank, the diluted polymer solution was pumped through the test-rig with the use of two pumps, one screw pump and one piston pump. Samples were taken downstream the Typhoon Valve with a fully open ball valve. The polymer solution went through the test loop at different flow rates and pressure heads, and with a temperature of 50 °C. The flow rates were adjusted manually with a computer. The viscosity of the samples was measured with a rheometer. The viscosity of the diluted polymer solution before entering the loop as well as the viscosity of the solution after it went through the loop (valve) were measured and compared.

4.1.2 Test program and procedures

The different test parameters are listed in table 4-1.

Test parameters Typhoon Valve									
Q (l/h)				dP [bar]					
2000	4000	6000	8000	5	10	15	20	25	30

Table 4-1: The different parameters used when testing the Typhoon Valve in France

Samples were taken for each flow rate and each different pressure drop, so 5 samples were taken for each flow rate with a needle valve. The sampling point was a non pressure region, so there was no pressure drop in the sampling device. The Typhoon Valve that was tested is illustrated in figure 4-2 below.
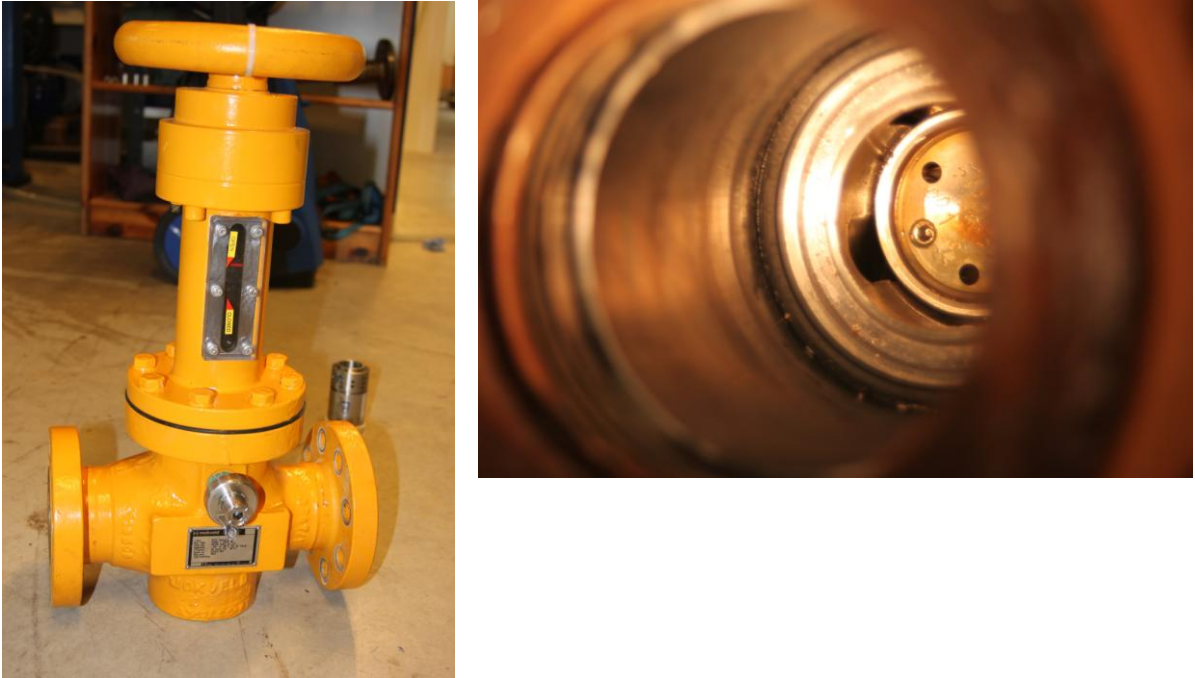
Figure 4-2: The Typhoon Valve tested in France

4.1.2.1 Polymer solution

The diluted polymer solution (800 ppm) was made from a mother solution. An illustration of the making of the mother solution is shown below in figure 4-2.

Preparation of the diluted polymer solution
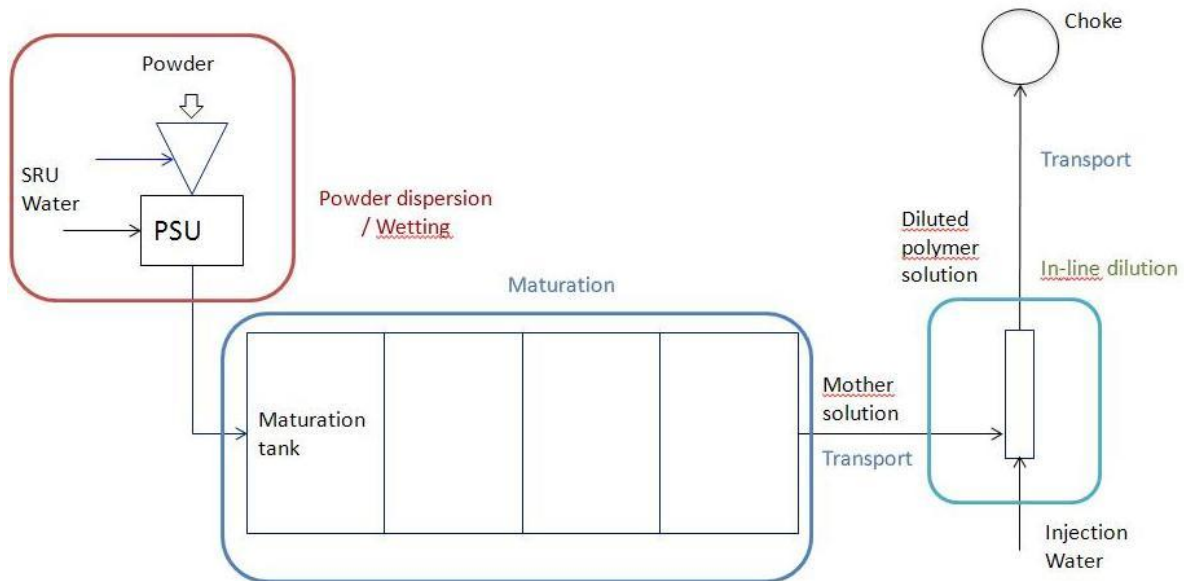
Figure 4-3: Preparation of polymer solution [52]

With reference to figure 4-3, polymer powder is dispersed in a water phase, very gently. From here, the solution is matured in a maturation tank, until the solution is homogenous. From the maturation tank, the mother solution is transferred and diluted with injection water, until the solution contains the desired concentration of polymer. In this test, it was a concentration of 800 ppm. The diluted solution is then transported or injected into the reservoir, or in this case, into the test-rig.

4.1.3 Viscosity analysis

The viscosity measurement of the samples were taken with a Brookefield DVII viscometer (Couette geometry), with an ULA adapter which can measure low viscosities [54]. A temperature controller, called a thermostatic jacket controls the temperature of the bob/cup, such that the temperature is constant, and in a suitable range for the samples. The viscosity were measured at different angular velocities (20, 30, 50, 60 and 100 rpm), where 1 rpm corresponds to a shear rate of 1.223 s^{-1}.

The samples (17 ml) were transferred to the cup, and the angular velocity was set on 20 rpm for 1 minute for temperature equilibrium at 50°C. The angular velocity was then increased, from low to high velocity, and at each velocity, it was necessary to wait for 1 minute for the viscosity value to be stabilized. The degradation of the samples was calculated based on equation 4.1:

$$Deg \% = \frac{\eta_o - \eta_{deg}}{\eta_o - \eta_{H2O}} \, x \, 100 \qquad\qquad (4.1)$$

Where:

η_0 = viscosity of non-degraded solution

η_{deg} = viscosity of the degraded solution

η_{H2O} = viscosity of water (, 00063 Pa*s (0.63 cP) at 50 °C)

The degradation was calculated from the viscosity measurements done at 60 rpm, which corresponds to a shear rate of 73.38 s^{-1}.

4.1.4 Viscosity calculation

All the results and calculations from this test were done by Total.

4.2 Testing of coil (Shark), Typhoon Configuration and Standard Valve – Main Project

This testing is a part of the polymer degradation main project between Typhonix, Total (PERL), IRIS and the Research Council of Norway.

This chapter describes the methods and experimental procedures for mechanical degradation of polymers with coils, a Standard valve and a small scale Typhoon Valve. It includes description of the test rig, test-program, test-components, rheology analysis and polymer solution mixtures. The Shark was not tested; instead cones and a coil were tested, which has the same principles of function as the Shark, with the same benefits with respect to shear rates and turbulence. This means that the results withdrawn from the testing can be directed to the Shark with respect on mechanical degradation of polymer.

4.2.1 Test rig functionality

To study the mechanical degradation of polymers with the chosen flow control devices, a test-rig was built in the Typhonix laboratory at Varhaug.

The rig, together with the test parameters, is illustrated in figure 4-3.

Pressures	Tests	Flows (l/h)
5 bar 10 bar 15 bar 20 bar	Pump caracterization	1000 600 200
Meassured	A (6,8,10,12,15mm)	1000 800 600 400 200
0 bar 5 bar 10 bar 15 bar 20 bar	Standard valve caracterization	400
Meassured	A (8mm) H (8mm) Standard valve	1000 800 600 400 200
Meassured	Typhoon valve Standard valve	1000 800 600 400 200
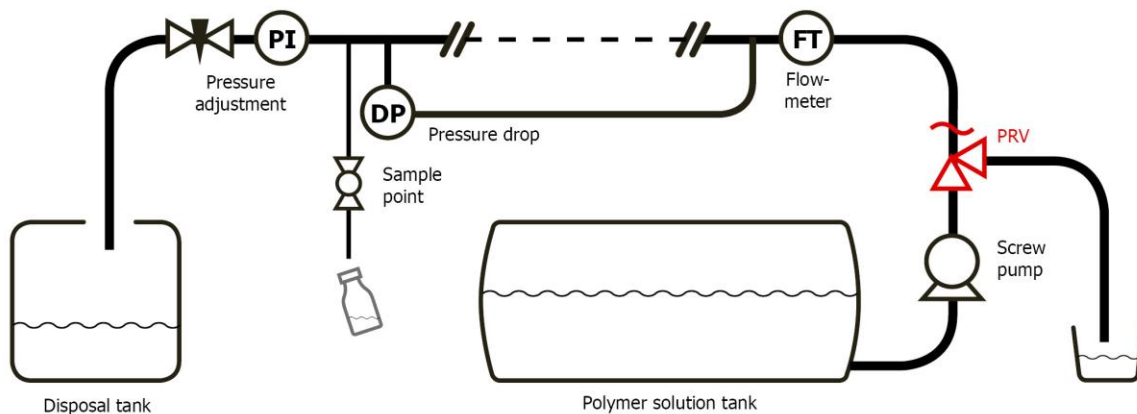
Figure 4-4: Illustration of the test-rig together with the different test components and test parameters

With reference to figure 4-4, polymer solution was mixed in the polymer solution tank. The temperature of the polymer solution was held on 30 °C. An eccentric screw pump was used to pump the solution in the rig. The flow was measured with a flow meter, to see if the desired flow rate was achieved. From here, the flow went through the test section, where different test-components were tested. Pressure adjustment was done upstream the test-section with a needle valve. From the test-section, the flow went into a disposal tank. The test-rig together with the polymer tank and disposal tank is also pictured in figure 4-5 below.

Figure 4-5: The whole testing area, with the test-rig, polymer tank and disposal tank

After the test-rig was build, it had to be verified that everything in the rig functioned in a correct manner. The test-rig components also had to be flushed with clean water, to make sure that there was no oil residue or other pollutions in the rig, which would have contaminated the polymer solution. For this, the following procedure was followed:

1) Make sure that everything is closed (valves)
2) Fill the tank with hot water
3) Open the tank
4) Open the valves
5) Start the pump
6) The water will go through the rig, and out through the outlet hose
7) When the water is clean, stop the pump
8) The rig is now considered finished flushed
9) Close everything (valves)
10) The test-rig is now ready for polymer testing

The test-rig procedures for the other tests are described under each test sub chapter.

4.2.2 Test-rig Components
The test-rig contained different components, some of the most important ones are described in the subchapters below.

4.2.2.1 Polymer tank
The tank that was used to mix the polymer solution has a volume of 900 liters. The tank was originally a tank used for dairy products, and was delivered from TINE.

4.2.2.2 Eccentric screw Pump

The pump used in the rig is an eccentric screw pump. By adjusting the Hz in the pump, the flow rate could be controlled and adjusted. The % speed for the desired flow rates in the tests are listed in table 4-2 below, as well as an illustration of the pump in figure 4-6.

Q (l/h)	200	400	600	800	1000
% speed	18	35	53	71	89

Table 4-2: % pump speed used to achieve the desired flow rates with the eccentric screw pump

Figure 4-6: The eccentric screw pump used in the test-rig

4.2.2.3 Flow meter

The flow meter was set upstream the test-section, such that the flow rate could be monitored. The flow meter is illustrated in figure 4-7 below.

Figure 4-7: The flow meter used in the test-rig

4.2.2.4 *Testing components – Valves*

The components that were characterized with respect to mechanical degradation were the coils (Shark), the Typhoon Valve and a Standard valve. To highlight the positive effect the coils and the Typhoon valve might have on mechanical degradation, their effect on degradation were compared to a Standard valve.

4.2.2.4.1 Coils

For the mechanical degradation of polymers with coils, cones of different cross sectional area were tested. The different diameter of the cones are listed in table 4-3, and illustrated in figure 4-8 below.

Cone Dimensions					
OD (mm)	6	8	10	12	15
ID (mm)	4	6	8	10	12

Table 4-3: Cone dimensions used in the testing
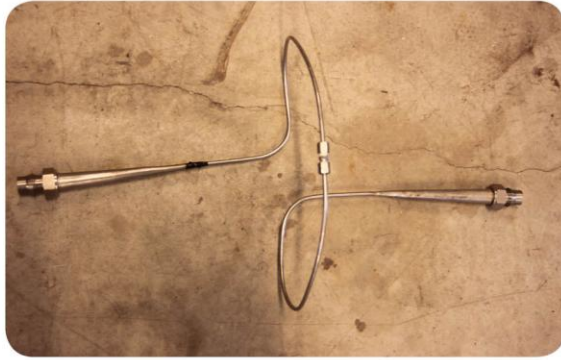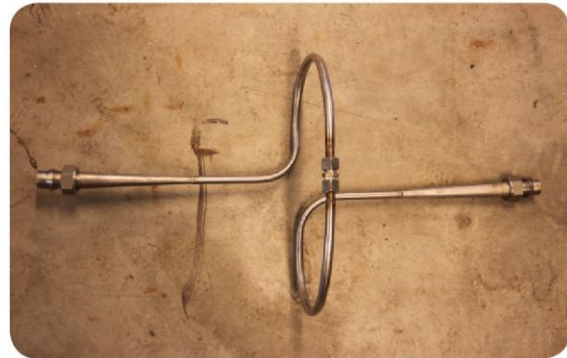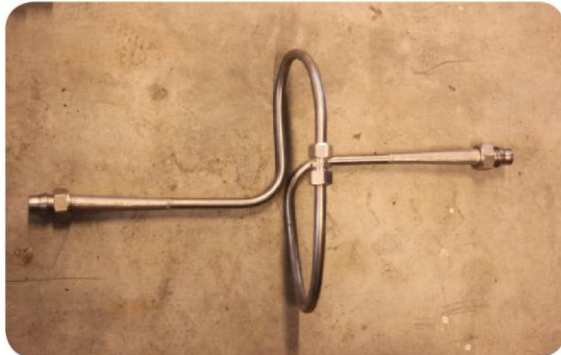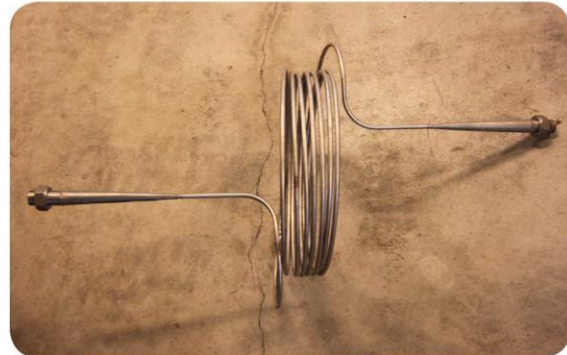
Figure 4-8: The different cones and coil tested

The reason why different diameters were tested is because cones/pipesw of different cross sectional area will give different pressure drop across the cone, hence the shear rates will differ in the different cones. The pressure drop will have an influence on shear, and hence, the degradation of the polymer solution. The 6 mm coil with high flow rate will give the highest shear rate, while the coils with larger diameter will give less shear rate. The cone dimensions, as well as the different flow rates were also used to calculate normalized viscosity which is described in chapter 4.2.5.3.

In this thesis, cone refers to one single loop, while the coil refers to the spiral. The spiral was tested to see if longer length had an influence on mechanical degradation of the polymer solution.

4.2.2.4.2 Typhoon Valve

Mechanical degradation was studied with a small scale Typhoon Valve. The Typhoon Valve originally planned to be use had to low pressure drop across the valve, so modifications were done to the valve. To increase the pressure drop, the cage was taped, such that only a few holes were open for passage of polymer solution. However, even then, the pressure drop was only 1.72 bars at 1000 l/h, so a new Typhoon valve configuration had to be used. This valve is showed in figure 4-9 below. With this valve configuration, the pressure drop was increased to 8.17 bars at 1000 l/h.

Figure 4-9: The Typhoon valve configuration inserted in the test section of the test-rig

4.2.2.4.3 Standard Valve

The Standard valve that was testes is illustrated in figure 4-10 below. This valve was tested at the same conditions (flow rate and pressure drop) as the coils and the Typhoon Valve configuration for comparison of mechanical degradation of polymer solutions.
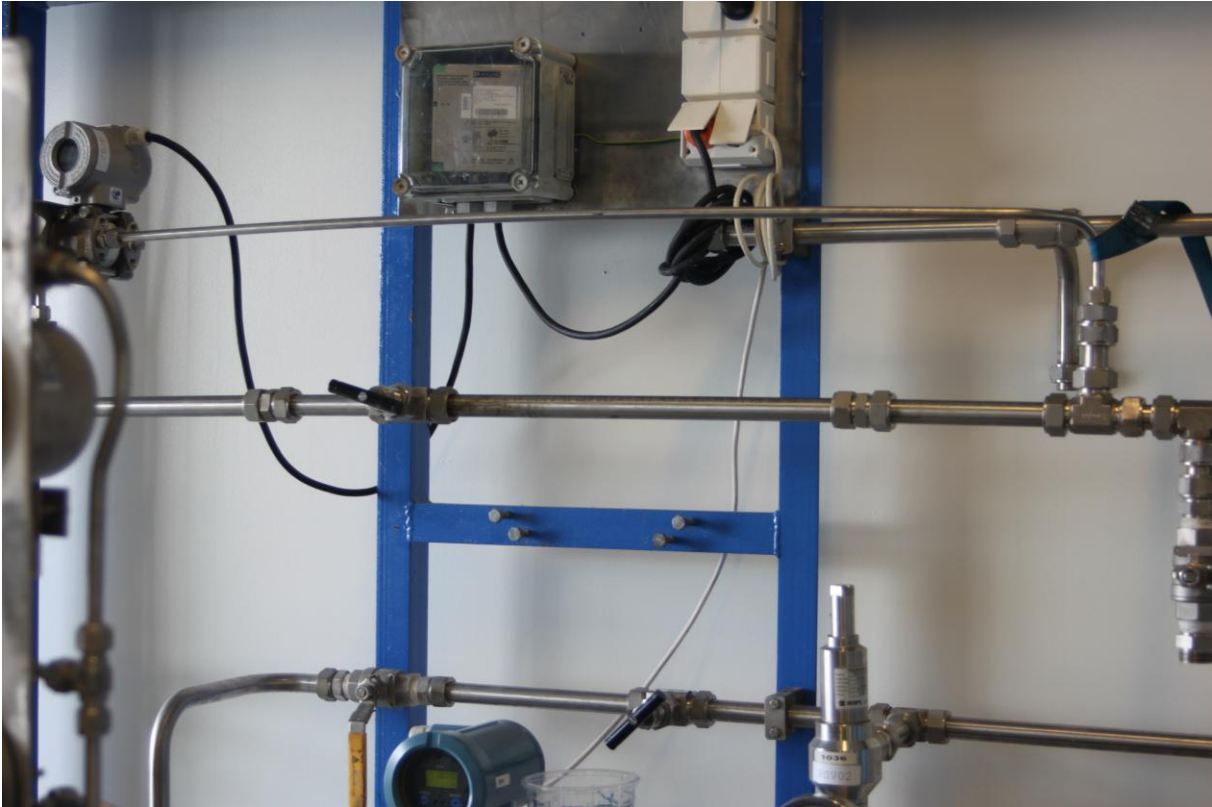
Figure 4-10: The Standard valve installed in the test-section of the test-rig

4.2.2.5 Sampling point

The samples were taken with a ball valve downstream the test section. The samples were taken by opening the valve, flush it, and then collect the sample in a bottle. An illustration of the valve and the sampling is shown in figure 4-11 below.

Figure 4-11: Sampling of polymer solution downstream the test-section

4.2.3   Mixing of Polymer solution

The polymer that was used is from SNF Floenger, and is named FLOPAAM 3630 S. To study mechanical degradation of polymer solution, the concentration of the solution has to be quite high such that there is a big difference in viscosity between clean water and the polymer test solution. The chosen concentration of the polymer test solution was set to 1000 ppm.

4.2.3.1   Mixing verification

Mixing of polymers may be a difficult task because it is so shear sensitive. In addition, there has to be a relative high mixing speed during the mixing, especially at the beginning, to make sure that the polymer is appropriate mixed in. If there is not enough mixing speed, the polymer will cluster together and make gel clumps in the water, which makes the solution non-homogenous. To see if the test tank gave the right amount of mixing, a mixing test was done in advance of the testing in the rig with the use of a hand mixer, which had the same mixing speed as the paddle in the test tank. Polymer solutions were mixed with high speed, low speed, and very low speed.

A hand mixer was used to mix polymer solution of 1000 ppm. Polymer (1 g) was gently poured into water (1000 g) with high speed, low speed and very low speed respectively. The solutions were mixed for 2 hours. Too see if the solution was homogenous after the mixing, the solution was poured into a settling cone, to see if the solution settled. Viscosity analysis was done afterwards, to see if the different mixing speeds gave the same viscosity of the solution. It was taken two parallels from each solution, so in total 6 viscosity measurements were done. From the settling cone, two different samples were taken from the same solution,

to see if each sample gave the same viscosity. This verified that the solutions were homogenous, and that the solution was well mixed with the use of a hand mixer.

According to IRIS, which is part of the project and experts in this field, the mixing speed which is used to give the right mixing for a homogenous polymer solution is 1 hour at 700 RPM, 2 hours at 300 RPM, and then over night at a stirrer. It is especially important to create a vortex when the polymer powder is poured into the water, if there is no vortex, clustering of polymer gel clumps occur, which make a non-homogenous solution.

The results showed that both the high mixing speed, low mixing speed and very low mixing speed gave approximately the same viscosity. It was at first thought that the tank did not have sufficiently mixing speed for the polymer solution. However, based on the these results, it was assumed that test tank could be used to mix the polymer solution, due to the fact that the low mixing speed with the hand mixer gave the same viscosity of the solution as the high mixing speed. Viscosity results from the tests are shown in figure 4-12 below.
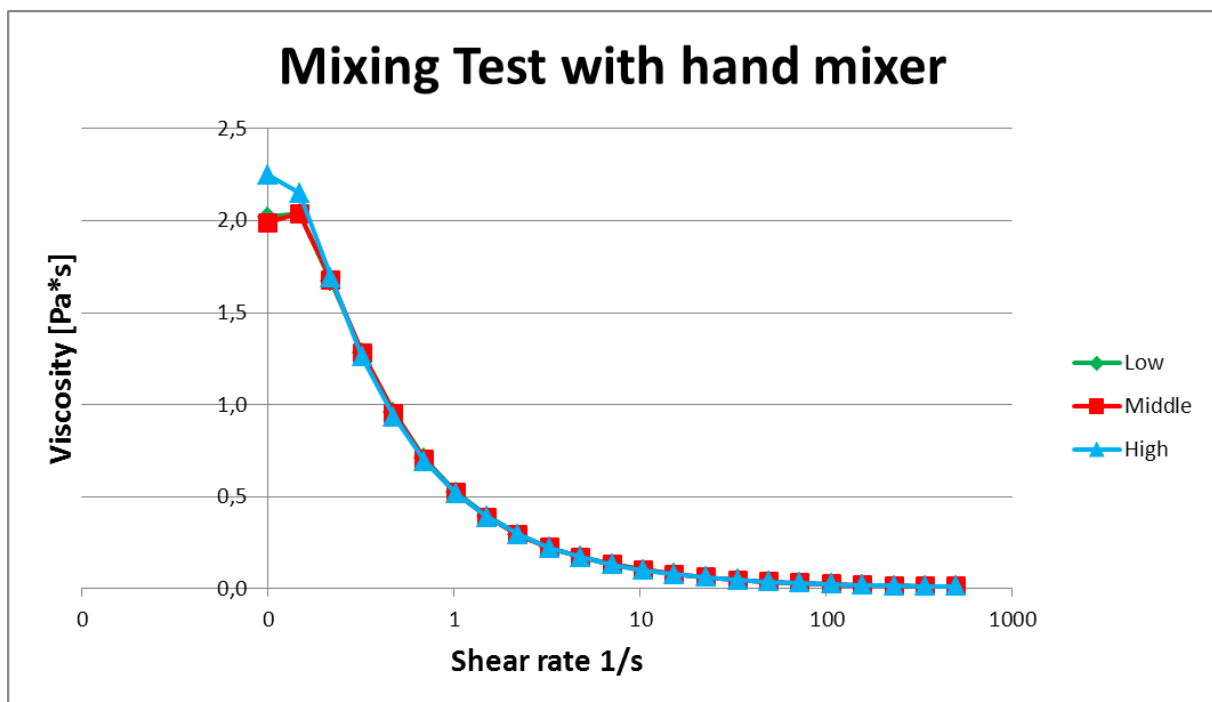
Figure 4-12: The viscosity as a function of shear rate for three different solutions mixed at different speeds

As can be seen from the graphs, the viscosity is approximately the same for all three solutions.

After this assumption was made, a polymer solution was made in the tank. Polymer (300 grams) was poured gently into the water in the tank (300 liters), and the solution was mixed overnight. Three different samples were taken the next day from different locations in the tank, and all three samples had approximately the same viscosity. This verified that the tank

was capable of mixing polymer solution, and that the solution was homogenous. The viscosity results from the tank samples are shown in figure 4-13 below.
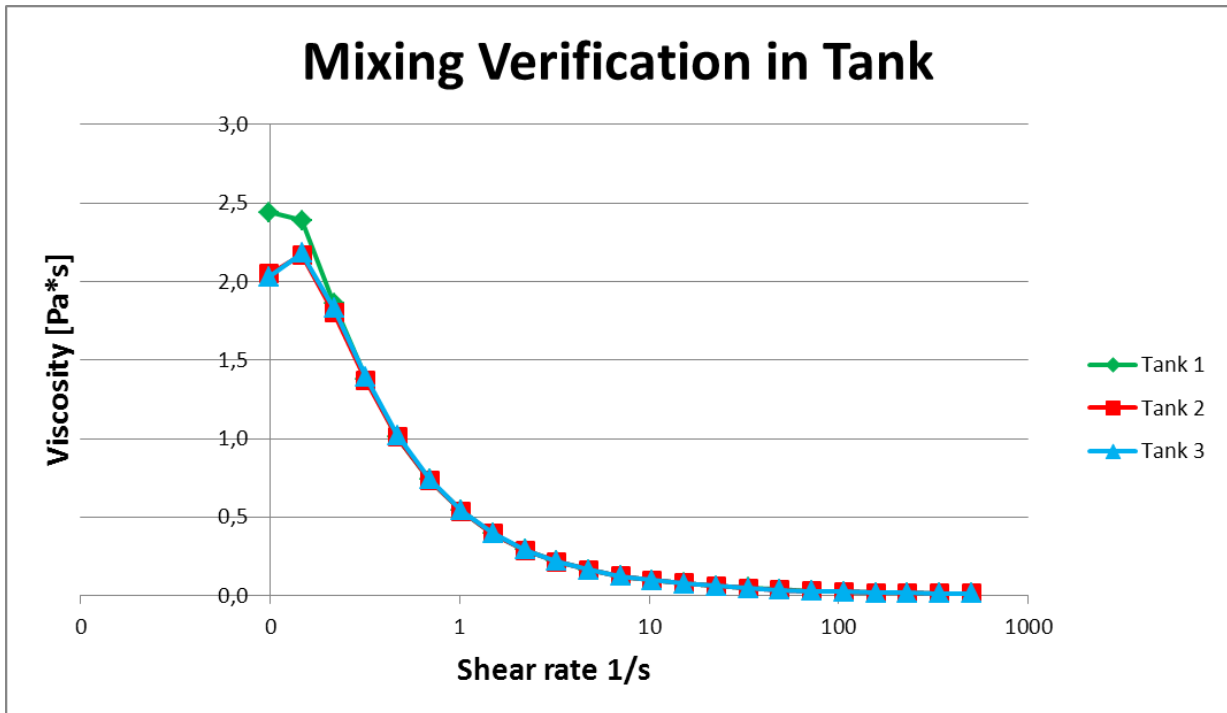
Figure 4-13: The viscosity of three different samples taken from the solution in the tank

The procedure for viscosity analysis is described in chapter 4.2.5.

4.2.3.2 *Mixing of polymer solution in the tank*

The amount of polymer needed to obtain the desired concentration of 1000 ppm is 1 g polymer per 1000 g water. In the beginning the idea was to mix 900 liters of polymer solution, because that is the tank volume. However, during test mixing in the tank, it was seen that the paddle did not rotate fast enough for such high volumes, so the solution was not sufficiently mixed, and big gel clumps clustered together. The new idea was to use smaller volume, to get more turbulence and better mixing of water and polymer in the tank. The new volume was set on 300 liters. For a concentration of 1000 ppm polymer in 300 liters of water, the amount of polymer needed is 300 gram. This was calculated as follows:

1000 ppm = 0.1%
1 kg water = 1000 gram
1000 g water x 0.1% / 100 % = 1 gram
So, 1 gram polymer per 1000 gram of water.

300 liter water x 1000 g = 30000 gram of water
30000 g water x 0.1 % / 100 % = 300 gram

So, 300 gram polymer per 30000 gram of water.

For the tank, 300 gram of the polymer was poured gently into the tank, while the paddle was stirring. The polymer solution was then mixed over night, to make sure that the polymer was well mixed in such that the solution was homogenous.

4.2.3.3 *Homogenous solution verification*

Before each test, the viscosity of the solution in the tank was measured, to make sure that the solution was homogenous. The verification of a homogenous solution is extremely important such that the viscosity is approximately the same during all the tests, in addition, it is very important to know the viscosity of a non-degraded solution, such that % degradation can be calculated with equation 4.1 in chapter 4.1.3.

When a new solution was mixed in the tank overnight, viscosity analysis was taken of the solution. One sample was taken on the left side of the tank, and one sample was taken on the right side of the tank, and rheometer analysis was taken with both samples. It was taken two parallels of both samples, in total 4 viscosity measurements were done. If the samples had the same viscosity, it was determined and verified that the solution was homogenous. If the samples did not have the same viscosity, a new solution should be made.

4.2.4 *Test program, test-components and procedures*

The test program was split into five parts. The first part was pump characterization. This was done to see how much the pump contributed to mechanical degradation of the polymer solution. In the second part, the test-components were coils with different cross-sectional area. All the different coil sizes were tested at different flow rates, to determine which coil size and flow rate gave the highest degradation of the solution. In the third part of the test program, a Standard valve was characterized, to see if, and how much this valve contributed to mechanical degradation of the polymer solution. In the fourth part one of the coils from the second part were chosen and tested together with its spiral, and compared to a Standard valve which was tested at the exact same conditions (dP and Q) as the coil. In the fifth part of the test-program, a Typhoon Valve was tested at the same flow rates as in the other test-parts, and compared to a Standard valve which was tested at the exact same conditions (dP and Q) as the Typhoon Valve

4.2.4.1 *First part - Pump characterization*

Equipment like pumps may also contribute to mechanical degradation of polymer solutions during polymer injection. To see if, and how much the pump in the test rig contributed to mechanical degradation of the polymer solution, it was characterized in advance of the testing with the coils.

The test conditions in the pump characterization are listed in table 4-4 below. A sample was taken at each pump head and for every flow rate. The procedure for pump characterization in the test-rig was as follows:

Test parameters Pump Characterization							
Q (l/h)			dP [bar]				
200	400	600	0	5	10	15	20

Table 4-4: The test parameters for the pump characterization

1) Check that everything in the test-rig function properly, and that everything is OK
2) Measure that the solution temperature is 30 °C
3) Start the pump, adjust the % pump speed to achieve the desired flow rate. E.g 18 % to achieve a flow rate of 200 l/h
4) Check in the flow meter that the pump is giving the desired flow rate
5) Adjust the pressure to the desired pressure, e.g 5 bars
6) With low flow rates, like 200 and 400 l/h, wait a couple of minutes before taking the sample, to be sure that the flow has reached the test section
7) When the flow has reached the test-section, take the pressure down to 0 bars
8) Wait until there is no pressure, before taking the sample
9) Take sample by opening the valve, flush it, then take the bottle under the fluid stream until you have enough sample, take the bottle away, and then close the valve
10) The sample has been taken, adjust the pressure to the next desired pressure, e.g 10 bars, and repeat the procedure
11) When samples has been taken at every pressure head at a given flow rate, adjust the pump Hz to get the next desired flow rate
12) Repeat the procedure for the next flow rates

In total, 15 samples were taken.

4.2.4.2   Second part - Cone sizes

Cones of different cross sectional area (table 4-3) were tested at different flow rates. The test parameters used in this test is given in table 4-5 below.

Test parameters – Cone sizes					
Q (l/h)					dP [bar]
200	400	600	800	1000	Measured during testing

Table 4-5: The test parameters used during cone testing

The 6 mm cone was tested first, and the 15 mm cone was tested at the end. The same procedure was followed for every coil size, the only difference was the pressure drop, due to differences in cross sectional area of the cones. The procedure was as follows:

1) Check that everything in the rig is OK, and that the components function properly
2) Measure that the solution temperature is 30 °C
3) Start the pump, adjust the % pump speed to achieve the desired flow rate for the test
4) Check in the flow meter that the actual flow rate equals the desired flow rate
5) Read dP [bar] over the cone

6) With low flow rates, like 200 and 400 l/h, wait a couple of minutes before taking the sample, to be sure that the flow has reached the test section
7) Take sample by opening the valve, flush it, then take the bottle under the fluid stream, take the bottle away, and then close the valve
8) The sample has been taken, adjust the % pump speed to get the next desired flow rate.
9) Repeat the procedure for the next flow rates
10) When there has been taken samples at every flow rate, then change the coil in the test section to a new coil, e.g from 6 mm to 8 mm cone
11) Repeat the procedure with the new coil
12) Repeat the procedure until all the coils are tested

An illustration of a cone inserted in the test-rig is given in figure 4-14 below.

Figure 4-14:Cone (12mm) installed in the test-rig

At first, the plan was to test the different cones, then choose one of them, and test the chosen one with different cone angles, to see if different angles had a positive or negative effect on degradation of the solution. The angles that were supposed to be tested together with the chosen cone were 180°, 15° and 5°. The purpose was to see if contraction and expansion could have an effect on mechanical degradation. However, the tests with the cones did not give the results that were assumed, so there was no point in performing more tests with cones and different cone angles, because it would have no effect. The different configurations with different angles that were planned to be tested are illustrated in figure 4-15 below (A-I).
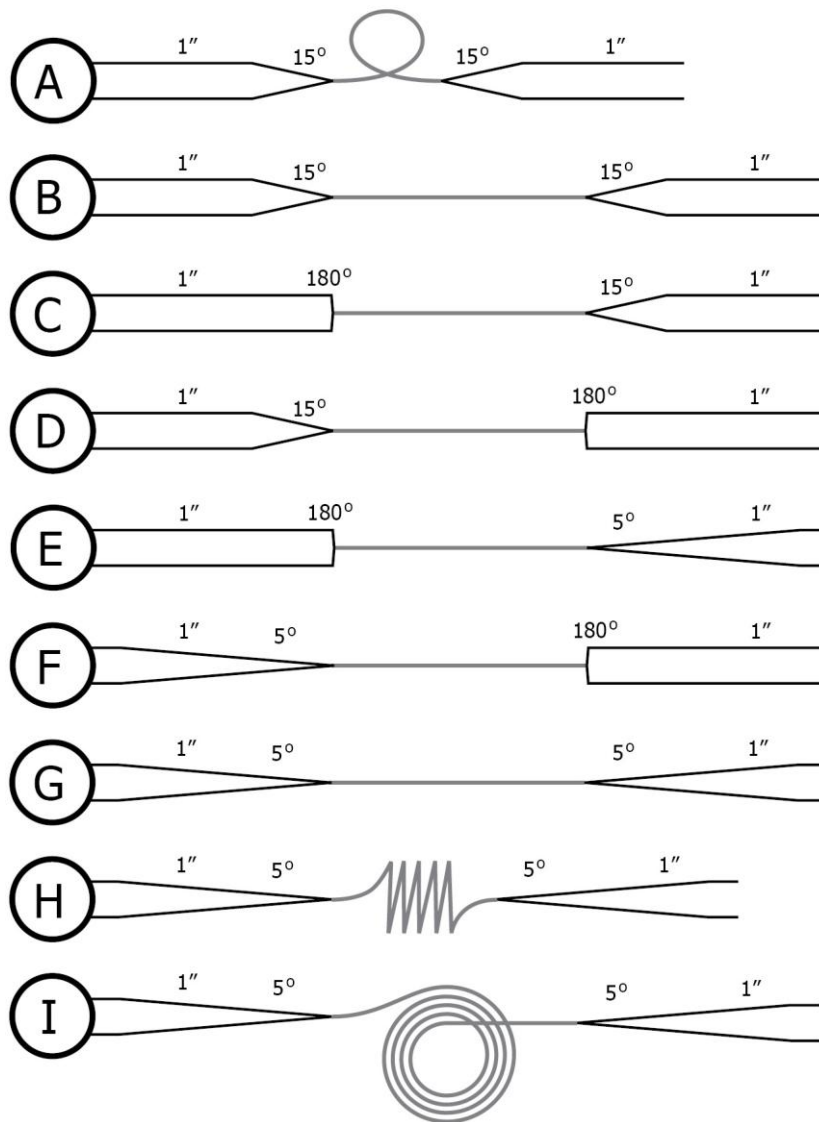
Figure 4-15: Contraction and expansion

Due to the fact that the cones did not degrade the solution, it was now decided to test one of the cones with a coil, and a standard valve at exact same conditions, to compare the effect of degradation by both the coil and valve. Further, it was decided to test a standard valve and a Typhoon valve at exact same conditions, to see if, and how much each valve degraded the polymer solution. These tests are described in the following sub chapters.

4.2.4.3 Third part - Standard Valve Characterization

Due to the fact that the test program was altered, a standard valve had to be characterized such that the new tests with comparison of coils and standard valve could be done.

A standard valve was tested to see if degradation occurred in this valve, and if so, how much. The test parameters used during the test is listed in table 4-6 below.

Test parameters Standard Valve characterization					
Q (l/h)	dP [bar]				
400	0	5	10	15	20

Table 4-6: Test parameters for Standard Valve Characterization

For the testing in the test-rig, the following procedure was followed:

1) Check that everything in the rig is OK, and that the components function properly
2) Measure that the solution temperature is 30 °C
3) Start the pump, adjust the % pump speed to achieve the desired flow rate for the test
4) Check in the flow meter that the actual flow rate equals the desired flow rate
5) Read dP [bar] over the valve
6) Adjust the pressure to the desired dP [bar]
7) Wait a minute to be sure that the flow has reached the test section
8) Take sample by opening the valve, flush it, then take the bottle under the fluid stream, take the bottle away, and then close the valve
9) The sample has been taken
10) Adjust the pressure to the next desired dP [bar]
11) Take sample as in point 6
12) Repeat the steps for the next desired pressure
13) When finished, turn of the pump

In total, 5 samples were taken.

4.2.4.4 Fourth part – Coil and Standard Valve

From the second test-part, a cone was chosen, which was tested alone and together with a coil. The two different test configurations is illustrated in figure 4-16 below (A and H), original a part of the test program original planned perform (A-I), see figure 4-14 in chapter 4.2.4.2.
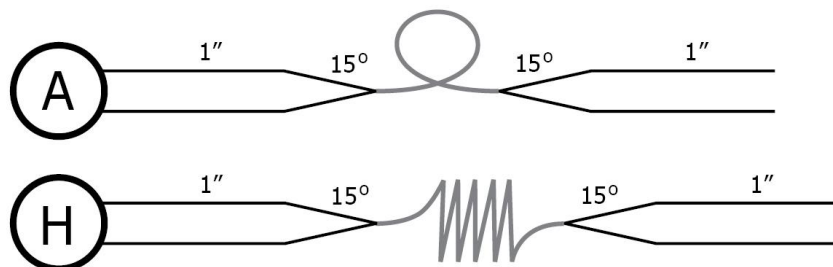
Figure 4-16: The test-components for the fourth test program, a chosen cone (A) and the coil (H)

The test parameters for this test are listed in table 4-7 below.

Test parameters Spiral and Standard valve Comparsion					
Q (l/h)					dP [bar]
200	400	600	800	1000	Measured during testing

Table 4-7: The test parameters when testing and comparing the spiral and Standard valve

When the coil was tested, the different dP at each flow rate was noted. A standard valve was then tested, and compared with the results from the tests with the coil. The standard valve was tested at the same flow rates and the corresponding dP as the coil. The results were then compared. The following procedure was followed:

1) Check that everything in the rig is OK, and that the components function properly
2) Measure that the solution temperature is 30 °C
3) Start the pump, adjust the % pump speed to achieve the desired flow rate for the test
4) Check in the flow meter that the actual flow rate equals the desired flow rate
5) Read dP [bar] over the coil
6) With low flow rates, like 200 and 400 l/h, wait a couple of minutes before taking the sample, to be sure that the flow has reached the test section
7) Take sample by opening the valve, flush it, then take the bottle under the fluid stream, take the bottle away, and then close the valve
8) The sample has been taken, adjust the % pump speed to get the next desired flow rate.
9) Read dP [bar] over the coil
10) Repeat the procedure for the next flow rates
11) Repeat the procedure with the coil, and standard valve
12) With the standard valve, adjust the pressure to the pressure obtained with the coil for each flow rate

In total, 15 samples were taken.

4.2.4.5   *Fifth part - Standard valve and Typhoon Valve*

In this test-program, the Typhoon Valve was compared to a standard Valve. The test parameters are shown in table 4-8.

Test parameters Typhoon and Standard valve Comparsion					
Q (l/h)					dP [bar]
200	400	600	800	1000	Measured during testing

Table 4-8: The test parameters for the testing and comparison between Typhoon and Standard valve

When the Typhoon Valve was tested, the dP at each flow rate was noted. The standard valve was then tested, at the same flow rates, and at the same corresponding dP as the Typhoon Valve. The procedure for the tests was the same as in the second and third test-program.

In total, 10 samples were taken in this test.

4.2.5 *Viscosity measurements and calculations*

The viscosity of the samples was measured with an Anton Paar Physica MCR rheometer.

The Anton Paar Physica MCR 101 is a rheometer which offers both rotational and oscillatory modes [3]. The rheometer is equipped with an EC motor technique, low friction bearing and a patented normal force sensor which has been optimized over years. A wide range of temperatures can be applied (-150 °C to +1000 °C), in addition to application-specific accessories. Figure 4-17 below shows an Anton Paar MCR rheometer, as well as the rheometer used during viscosity analysis.

Figure 4-17: A standard Anton Paar rheometer (left) [4] and the rheometer used (right)

4.2.5.1 *Calibration*

The rheometer always has to be calibrated if there has been months since it has been used. During measurements, necessary protection (gloves, glasses etc) has to be used. The calibration procedure is listed below.

1) Turn on the compressor, and wait until the pressure is established
2) The filter for the MCR should be disconnected until the pressure is established. When the pressure is established, the filter can be connected
3) Turn on MCR 101
4) Open the cooling water to
5) The instrument will now go through the startup procedure, wait until the status is OK
6) Remove the transport safeguard by pressing:
   a) Online
   b) Ref
   c) The spindle head will now automatically go to the top (end stop)

d) Push the transport safeguard gently to the side
7) Connect the communication cable (LAN port) and open Rheoplus software
8) Press on DEVICE (rheometer symbol) to open the CONTROL PANEL fane, press then on INITIALIZE
9) Put in the bob, e.g low shear bob
10) Press "Reset normal force", and switch to the fane "Service"
11) Press "Motor adjustment"
12) Press "Start", press "Continue", press "OK" (sit very still) – press "OK" again
13) Swith to the fane "Control panel", press "Set zero gap", when the status says OK, drive the spindle head back to the endstop by pressing "Online" and "Ref" on the display
14) The rheometer is ready for use

4.2.5.2 *Procedure for viscosity measurements of polymer solutions*

For the viscosity measurements of the polymer solutions, the template called flow curve (Zero shear viscosity) was used, together with plate and measurement cone (CP60-1) [19].

The settings that were used are listed in table 4-9 below.

Measuring points	23
Time unit	s
Duration measuring	20 s
Interval	460 s
Y - unit	Shear rate (1/s)
X – unit	Viscosity (Pa*s)
Initial shear rate	0.1 1/s
Final shear rate	500 1/s
Slope	5.947601 pt/dec

Table 4-9: settings used during viscosity measurements

The rotational velocity was increased from 0.1 s^{-1} to 500 s^{-1} for each sample. The procedure for viscosity measurements was as follows:

1) Calibrate the instrument
2) Set the Peltier element on 20 °C
3) Pipette polymer solution (5 ml) from the bottle and pour it onto the plate
4) Press measurements position
5) Set the settings as shown in table 4-9 above
6) Press start test
7) Wait until the measurements are finished
8) Save all the data
9) Read the viscosity at the shear rate of 0.317 s^{-1}

In the beginning, the same sample was measured twice, to see if both measurements gave the same viscosity. However, when it was clear that all the parallels gave approximately the same viscosity, it was decided to only take on measurement of each sample. The viscosity measurements were time consuming (7.40 minutes of one sample), so by taking only one measurement of each sample, time was saved.

4.2.5.3 Rheometer analysis and calculations

When the viscosity measurements had been done in the rheometer, the results were analyzed, and % degradation was calculated. Information about viscosity measurements and calculations has been given by Arne Stavland (IRIS) and Stephane Jouenne (Total) [53, 54].

The raw material obtained from Rheoplus were the viscosity (Pa*s) at different shear rates, in addition to a graph were viscosity was plotted as a function of shear rates (s^{-1}). This is illustrated in figure 4-18 below. The figure shows how the raw data is represented in the Rheoplus program.
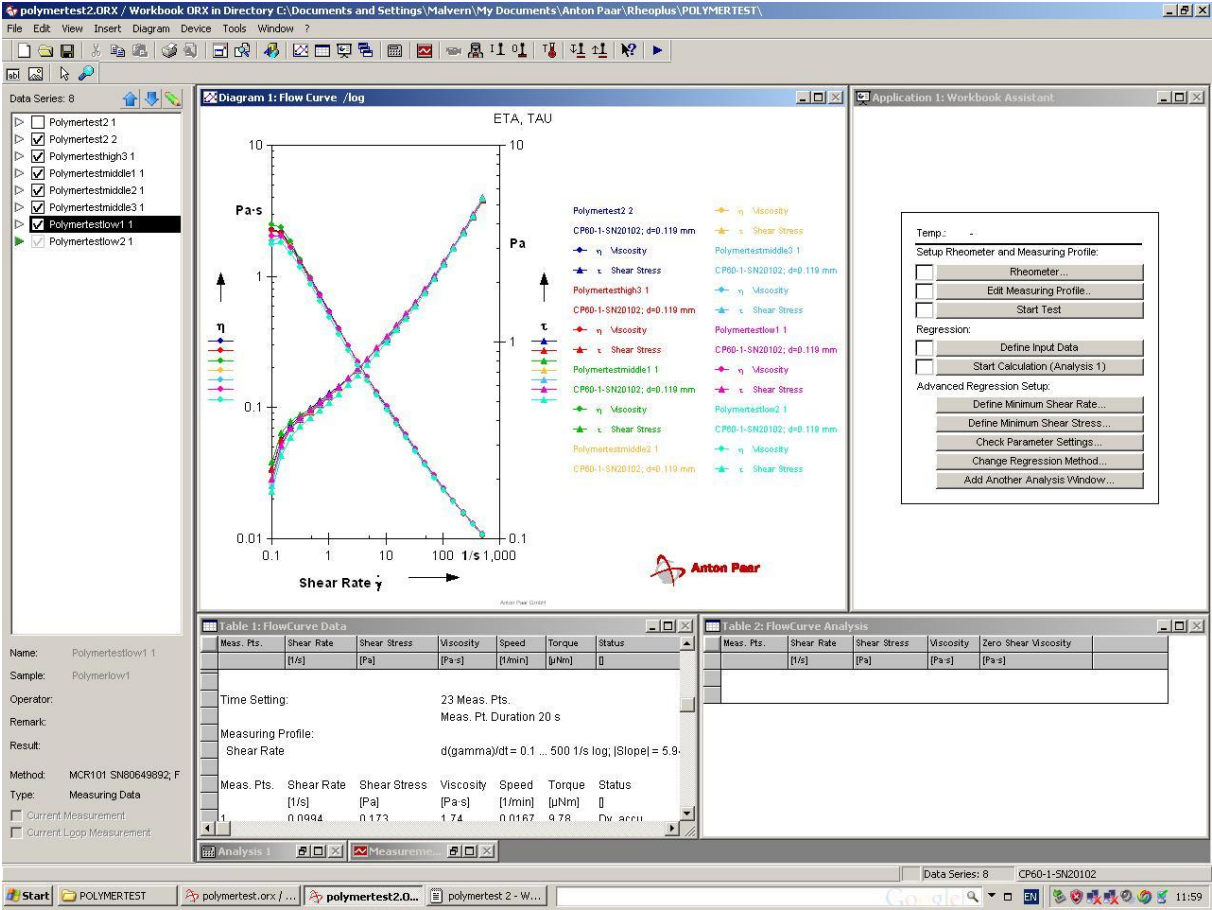
Figure 4-18: Screen shot from Rheoplus during a viscosity measurement

All the raw material was then transferred to Excel, where the measurements were further treated. New graphs were made. One graph in which viscosity was a function of logarithmic shear rate, and another graph in which % degradation was a function of either flow rate or

pressure head, at two different shear rates. A print screen of the excel sheet is illustrated in figure 4-19 below.
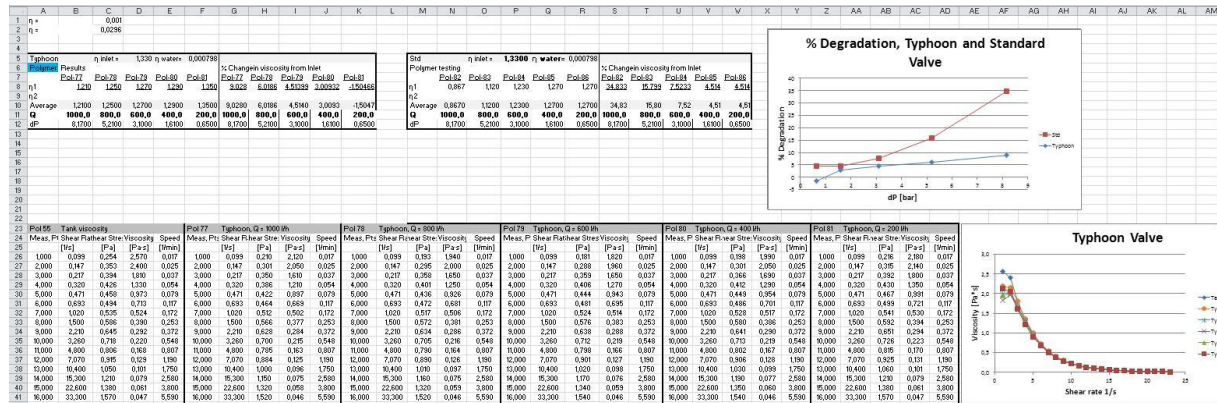
Figure 4-19: A screen shot of the excel sheet used for raw material treatment

For the calculations, it was decided to calculate % degradation at two shear rates. As stated in chapter 2.8, the normal shear rate in reservoirs is between $5 - 10$ s^{-1}. To see what viscosity the different flow control devices (coils, standard and Typhoon valve) gives on these flow rates, % degradation was calculated at a shear rate of 7.070 s^{-1}. This shear rate is also used by Total, when they are calculating % degradation by valves. However, it is also normal to calculate % shear degradation at a low shear rate. IRIS normally uses the viscosity a shear rate of 1 s^{-1} in their calculations [54]. Due to this, it was also decided to calculate % degradation at a shear rate of o.317 s^{-1}. Equation 4.1 was used for the calculations.

$$Deg \% = \frac{\eta_o - \eta_{deg}}{\eta_o - \eta_{H2O}} \; x \; 100 \tag{4.1}$$

Where:

η_0 = viscosity of non-degraded solution

η_{deg} = viscosity of the degraded solution

η_{H2O} = viscosity of water (0.00798 Pa*s (0.78 cP) at 30 °C)

When the calculation was done, the % degradation was plotted as a function of either flow rate or pressure drop.

Due to uncertainties in the viscosity at low shear rates, the normalized viscosity was also calculated at the two different shear rates. Normalized viscosity can be calculated with equation 4.2 [54].

$$Normalized \; viscosity = \frac{\eta_{non-deg} - \eta_{H2O}}{\eta_{deg} - \eta_{H2O}} \tag{4.2}$$

Normalized viscosity is a parameter of how much the solution have degraded. If the normalized viscosity is approximately 1, almost no degradation have occurred, while if the normalized viscosity is approximately 0, then the solution is completely degraded.

In addition, the theoretical shear rate in each coil at each flow rate was also calculated, to see if shear degradation was to be expected or not. The polymer used start to degrade at a shear rate of 18000 s^{-1} [54], so by calculating the shear rate in each coil and at each flow rate, it was possible to predict if or how much degradation occurs. The theoretical shear rate can be calculated by equation 4.3.

$$Theoretical\ shear\ rate = \frac{4*Q}{3.14*r^3} \qquad (4.3)$$

Where:
Q = flow rate m/s
r = radius of the coil

The calculated normalized viscosity was then plotted as a function of the calculated shear degradation for each Q and in each coil. This resulted in new curves, which had a better match and with less uncertainties. The curves also illustrates at which shear rate most of the degradation occurs.

5 *RESULTS AND DISCUSSION*

The results are divided into two main sub chapters. The first sub chapter is the results from testing of Typhoon Valve at Total's facilities. The second sub chapter is the results from testing of coils and the Typhoon Valve configuration, together with a standard valve at Typhonix's own laboratory at Varhaug.

5.1 *Typhoon Valve – Pre Project*

All the results from the testing with the Typhoon Valve are elaborated by Total [27], but Typhonix personnel (Trygve Husveg and Mari Stokka) were a part of, and present during the testing at Total's division for polymer flooding in Lacq (September 2012). Discussion of the results took place at Typhonix's facilties, with all parties in the pre-project (Typhonix, Total, IRIS) present.

It was tested that no other process equipment in the test loop contributed to degradation of the polymer solution.

5.1.1 *Degradation with the Typhoon Valve*

Figure 5-1 below shows the % degradation of the polymer solution at Q = 8 m^3/h, and at different ΔP.
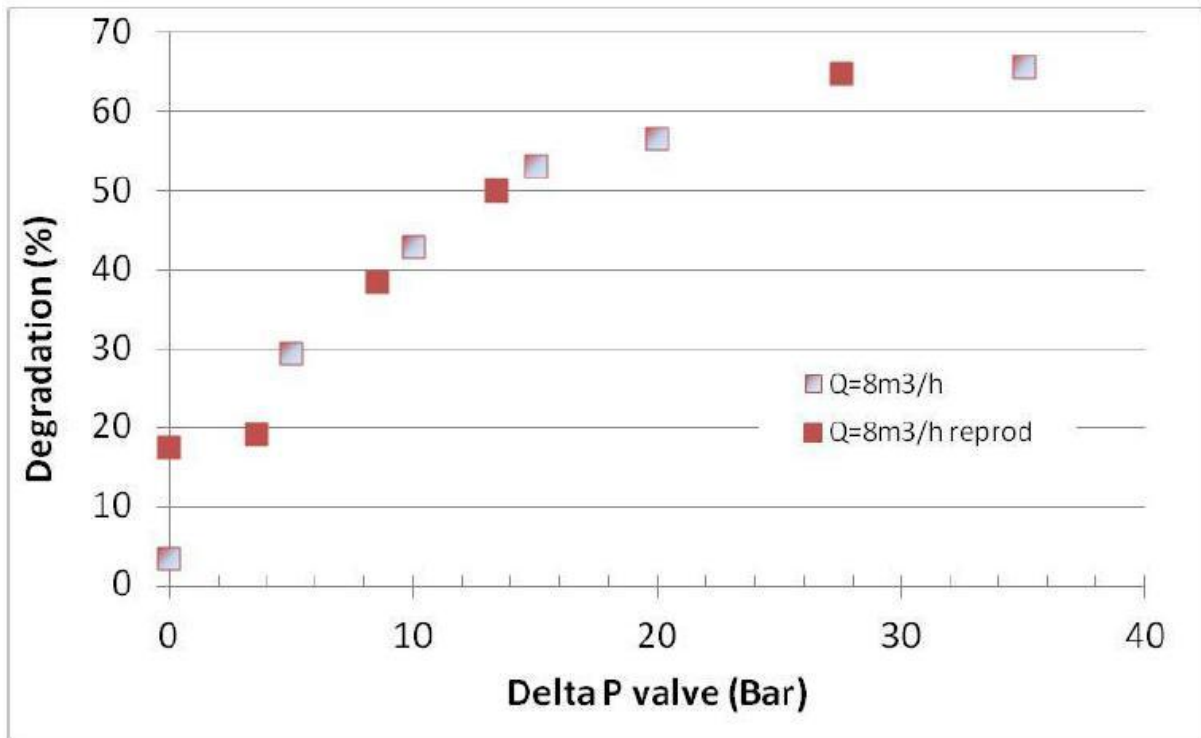
Figure 5-1: % degradation of polymer solution with Q = 8 m3/h with Typhoon Valve

From the graph, it is clear that the Typhoon Valve also gives a severe degradation of polymer solutions, especially at high delta P. Thr red dots in the graph is a second test, which show the exact same trends as the first test (white dots) with the Typhoon Valve. The viscosity of the solutions in both tests is approximately the same.

5.1.2   *Comparison between Standard valve and Typhoon valve*
A standard valve was also tested to compare the degradation within that valve with the degradation in the Typhoon valve. The % degradation of both valves are plotted in figure 5-2 below.
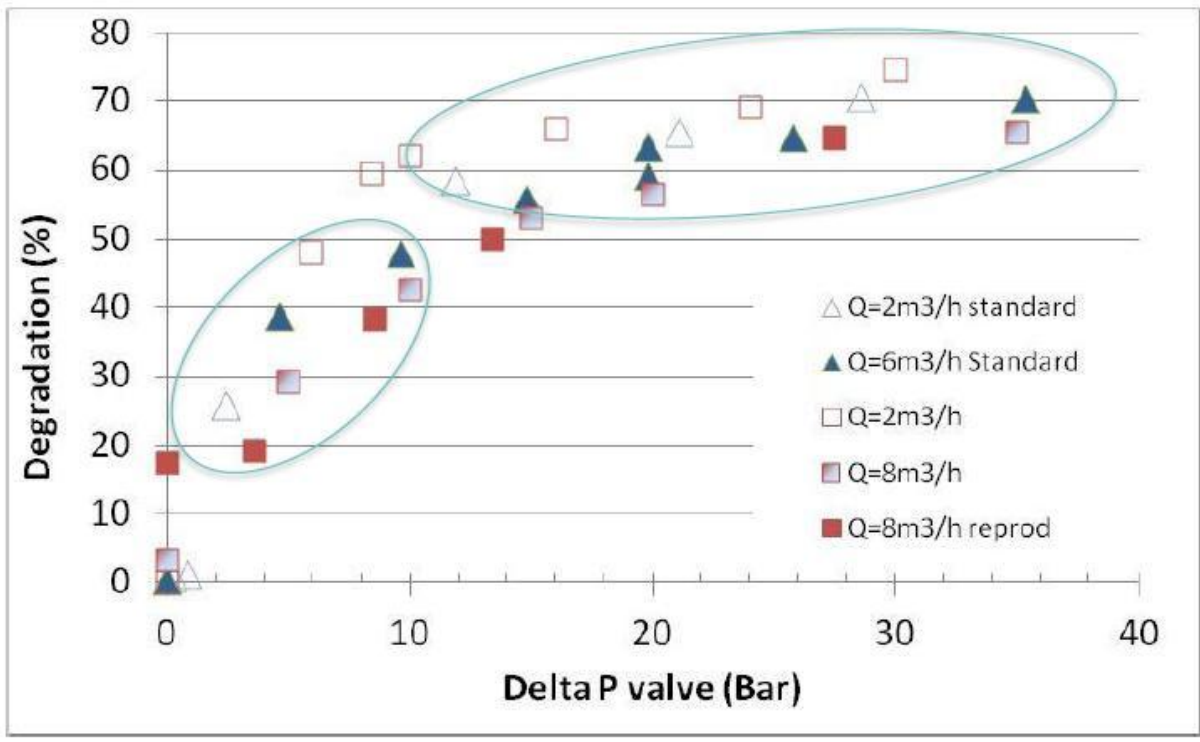
Figure 5-2: Comparison of % degradation between Typhoon and Standard Valve

As the graph shows, there is more degradation and shear in the Typhoon valve (white squares) at low flow rates, compared with standard valve (white triangles). When the flow rates increased, a small improvement with the Typhoon valve could be seen, but it is almost negligible.

5.1.3 Degradation at different flow rates and fixed delta P

Below, in figure 5-3 is the result from testing with different flow rates, but at two different fixed deltas P; 5 and 10 bars. The degradation for both the Typhoon valve and standard valve is plotted in the same graph.
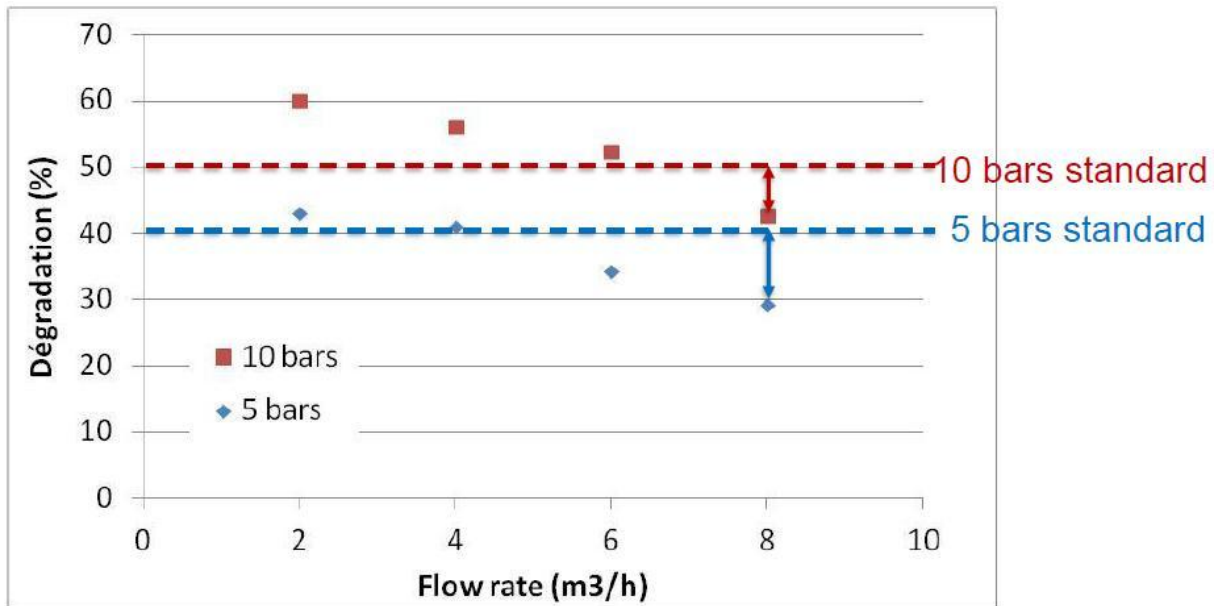
Figure 5-3: % degradation with Typhoon and Standard Valve

As can be seen from the graph, at low pressure drop and high flow rate, there is 10% less degradation with the Typhoon valve compared with standard valves.

5.1.4   Comparison between Typhoon Valve and Dalia choke valve

Dalia is one field among many others which have tried polymer injection and flooding. The valve they use is a choke valve. The field experience with injection at Dalia is described in chapter 2.6.2. Too se whether the Typhoon valve gave less degradation, these two valves were also compared, which is illustrated in figure 5-4 below.
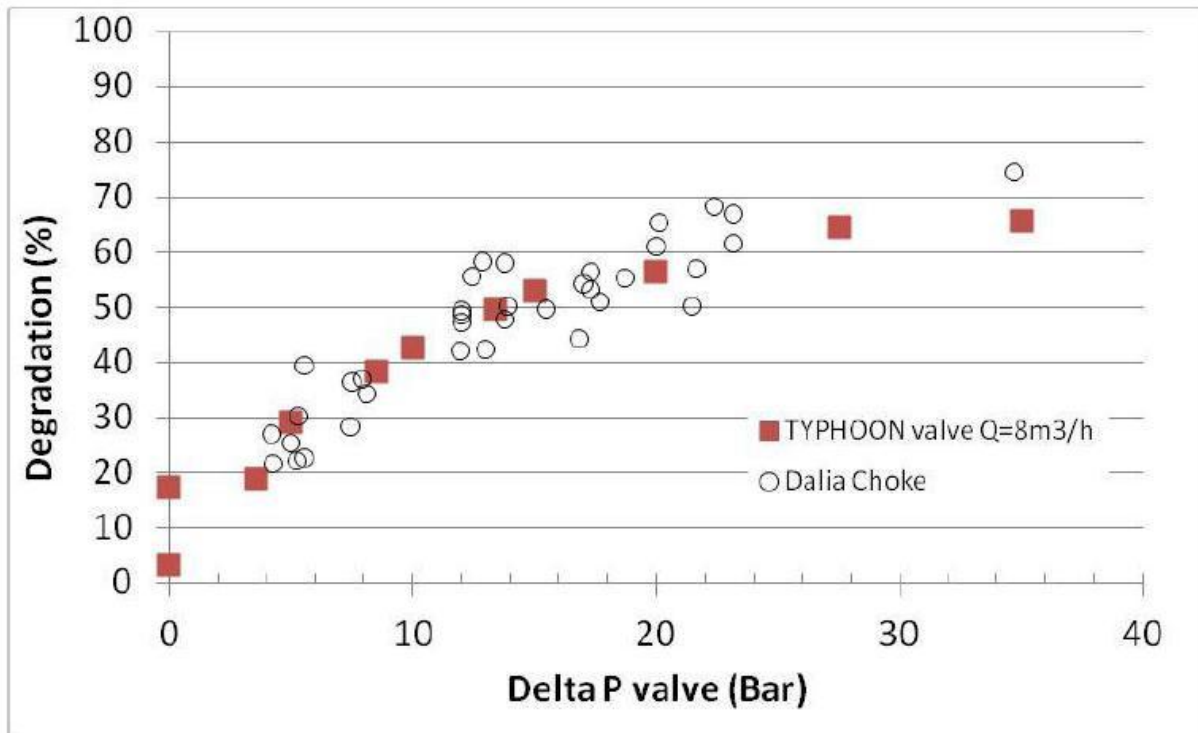
Figure 5-4: Comparison of % degradation between Typhoon Valve and Dalia choke

The % degradation with the Typhoon valve and the Dalia choke were very much similar, no improvements could be seen with the Typhoon valve. The % degradation increased as delta P increased for both valves, and reached values as high as 70 % degradation.

The same positive effect the Typhoon Valve has on coalescence and reduced oil droplet break-up was to be seen with reduced mechanical degradation of polymer solutions. The results from the testing with the Typhoon Valve were not as promising as it was thought to be. Due to the low shear in the valve, it was thought to minimize mechanical degradation to a greater extent then what it actually did, especially was it thought to reduce mechanical degradation compared to a standard valve.

With reference to figure 5-2, there is almost no difference in % degradation between the Typhoon Valve and standard Valve. At high pressures, such as 30 and 40 bars, both valves gave degradation up to 70%. The biggest difference between the valves was the % degradation at low and high flow rates. At low flow rate, it was more degradation with the Typhoon Valve than with the standard valve, this can be seen as the white squares and white triangles. However, at higher flow rates, like 6 and 8 m³/h, there is a small improvement; the Typhoon Valve gives a slightly less % degradation than the standard valve. This can be seen as the red dots and blue triangles, but the difference is so small, that it is almost negligible. The difference is highest at low ΔP, and lowest at high ΔP. At low ΔP, approximately 5 bars, the difference in % degradation between the two valves are almost 10%. At high ΔP however, approximately 20 bars, the difference in % degradation between the two valves is just a few percent, and at some ΔP, there is no difference at all. This trend can also be seen in figure 5-3. This curve shows the difference between the Typhoon valve and standard valve to a greater

extent. The blue and red dotted lines are the standard valve at 5 and 10 bars respectively, and the blue and white dots are the Typhoon Valve at 5 and 10 bars respectively. As can be seen, at low pressure drop (5 bars), and at high flow rates (6-8 m^3/h), there is a low shear effect with the Typhoon Valve. At these conditions, the % degradation with the Typhoon valve is 35 and 30 % respectively, while for the standard valve at the same conditions, the % degradation is approximately 50 and 40 % respectively. This is a difference larger than 10%. Also at 10 bars, and high flow rates (8 m^3/h), there is less degradation with the Typhoon Valve. At this condition, the Typhoon Valve gives approximately 40 % degradation, while the standard valve gives 50 % degradation at the same condition. As can also be seen in the graph, with the Typhoon Valve, the % degradation decreases as the flow rate increases. Tests should have been done with higher flow rates, to see if there is even less degradation at even higher rates, compared to a standard valve.

The Dalia Angola field uses a choke valve for polymer injection. A comparison between the Dalia choke and the Typhoon Valve is illustrated in figure 5-4 above. In the curve, the red squares represent the Typhoon Valve, while the white circles represent the Dalia choke. The % degradation is a function of ΔP. As can be seen from the curve, the % degradation is very similar for both valves at all ΔP. This means that the Typhoon Valve is not better than the already existing Dalia choke, no improvement was to see.

It was expected a significant reduction in degradation with the Typhoon Valve, compared to a standard valve, so the results were a disappointment. Even though there were a slight decrease in degradation with the Typhoon Valve, especially at low ΔP, and high flow rates compared to a standard valve, the results should be clearer and more conclusive. However, Stephane Jouenne from Total, claimed that the results were promising, and that further testing should be done. The 2" Typhoon Valve did not have an optimal capacity for the required pressure drop and flow rate. The internals in this valve was too closed, and the valve did not have optimal capacity. When the Typhoon Valve is too closed, there is not enough inlet moment to create the vortex, which is one of the main concepts with the Typhoon Valve. This means that all the pressure is taken over the cage, and the Typhoon Valve functions just like a standard Valve. The cage and venturi has to be optimized to create a strong and beneficial vortex flow through the valve. New testing with 2" Typhoon Valve with new internals should be performed, to see if the valve, with optimal capacity can reduce mechanical degradation of polymer solutions.

Another reason may be that the loop also contributed to degradation of the polymer solution. Even though it is claimed that other components in the loop did not degrade the solution, the sampling was somehow uncertain.Viscosity measurements of samples upstream the valve was not taken, so it is only an assumption that no degradation occurred in the loop. Samples should be taken before the valve as well as after the valve, to make sure that the only thing that contributes to mechanical degradation of the polymer solution actually is the Typhoon Valve.

The disappointing results however led to a new approach, which was testing of coils. It has been proven that coils and pipes enhances coalescence and reduces droplet break-up. As

described in chapter 2.7.3 and 3.7, the turbulence, and hence the shear rate can be controlled by adjusting the length in which pressure drop gradients can be reduced, as well as the diameter of the pipes. The new idea was to see if these coils also can contribute to reduced mechanical degradation of polymer solutions, by adjusting the length and the diameter of the pipes. Also, in the state of the art in polymer injection, there are technologies which take advantage of coils and pipes in polymer injection, and which are proven to be very promising with regard to degradation. One of the technologies which use coils is described in chapter 2.7.a and 2.7.3. Vladimir also demonstrated the positive coalescence effect with the use of coils in his bachelor thesis (chapter 3.9 and A.5). Due to this, it was thought that coils and pipes also can be used as flow control devices for polymer injection, with significant reduced mechanical degradation.

5.2   Coils (Shark), Typhoon Configuration and Standard valve – Main project

When the pre-project was concluded, it was decided to go further with a main project, with further testing of new internal in the Typhoon Valve, as well as testing of other low shear technologies (the Shark). The testing in this part is part of the main project between Typhonix, Total, IRIS and the Research Council of Norway.

The results are divided into five parts. First part consists of results from the pump characterization, the second part describes the results from the tests with different coil sizes and flow rates, the third part consists of the results from the tests with 8 mm coil and standard valve, while the fifth part consist of the results from the tests with standard valve and the Typhoon configuration.

The test scheme is to be found in appendix B, chapter B1, where every parameter is noted for every test sample.

5.2.1   First part - Pump Characterization

The methodologies for this test are to be found in chapter 4.2.4.1.

Three different flow rates were used together with ΔP of 0, 5, 10, 15 and 20 bars.
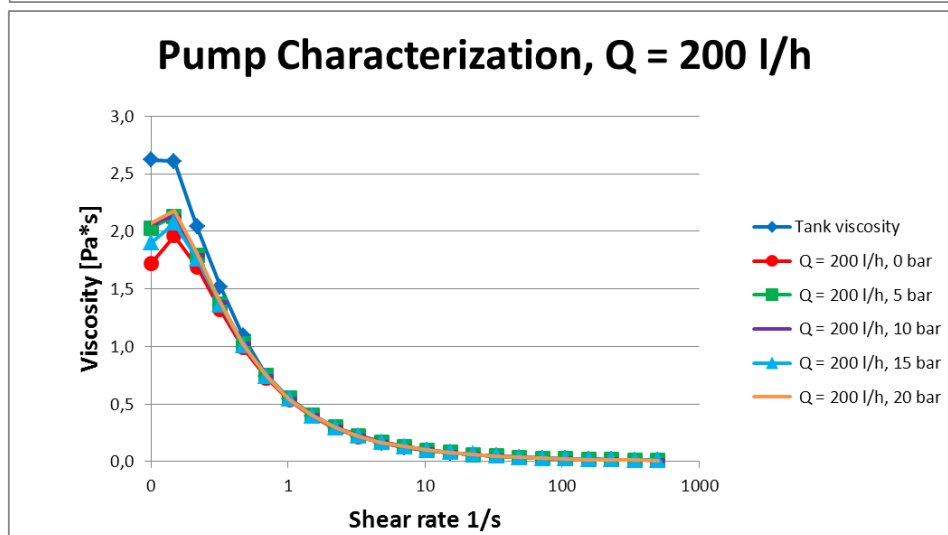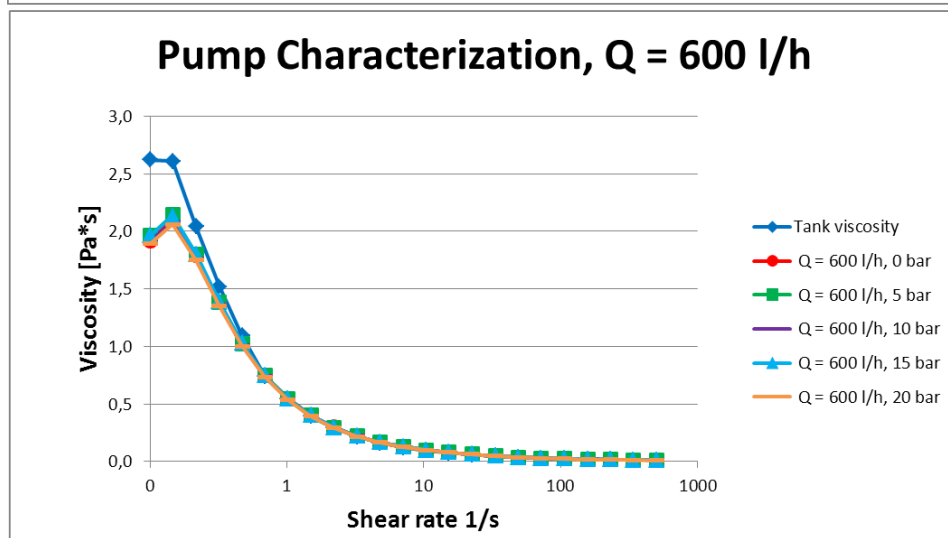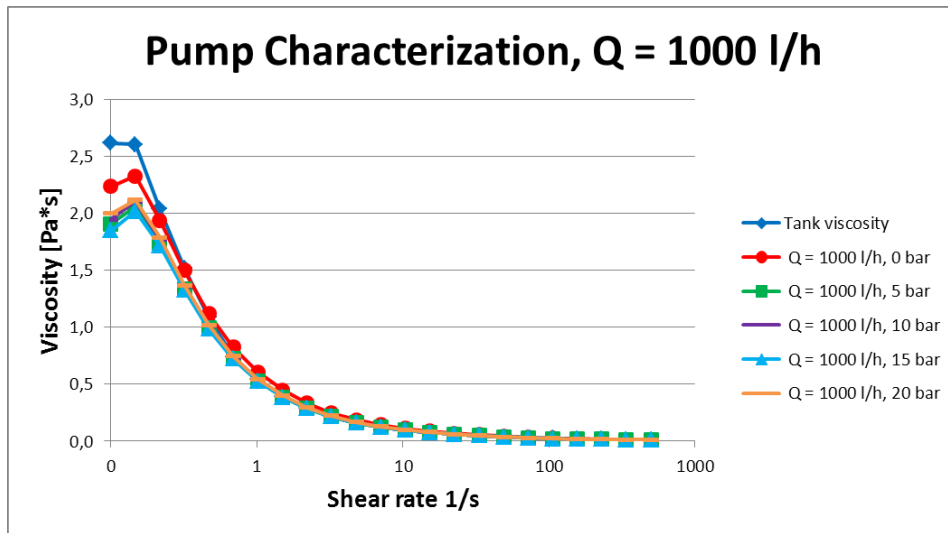
Figure 5-5: Pump characterization, viscosity plotted as a function of shear rate

It was seen that throughout the tests, the viscosity of the solution remained nearly constant. From figure 5-5 above, at every flow rate and dP, almost no degradation of the solution occurred. The only difference in viscosity is observed at low shear rates ($0.1 - 0.5$ s^{-1}) for the tests with low pressure drop, this can be seen in figure 5-5, where viscosity is plotted as a

function of shear rate for the different flow rates and dP. At higher shear rates, the viscosity of the different solutions is approximately the same as the viscosity for the tank solution, which is the dark blue line in the graphs. However, some degradation of the solution occurred, especially at low shear rates. From the figures, you can see that these viscosities differ to a larger extent from the tank viscosity, especially at a shear rate of $0.1 - 0.7$ s^{-1}. This means that some degradation occurs in the pumps. This can also be seen in figure 5-6 below, which illustrates % degradation in the pump as a function of pressure drop.
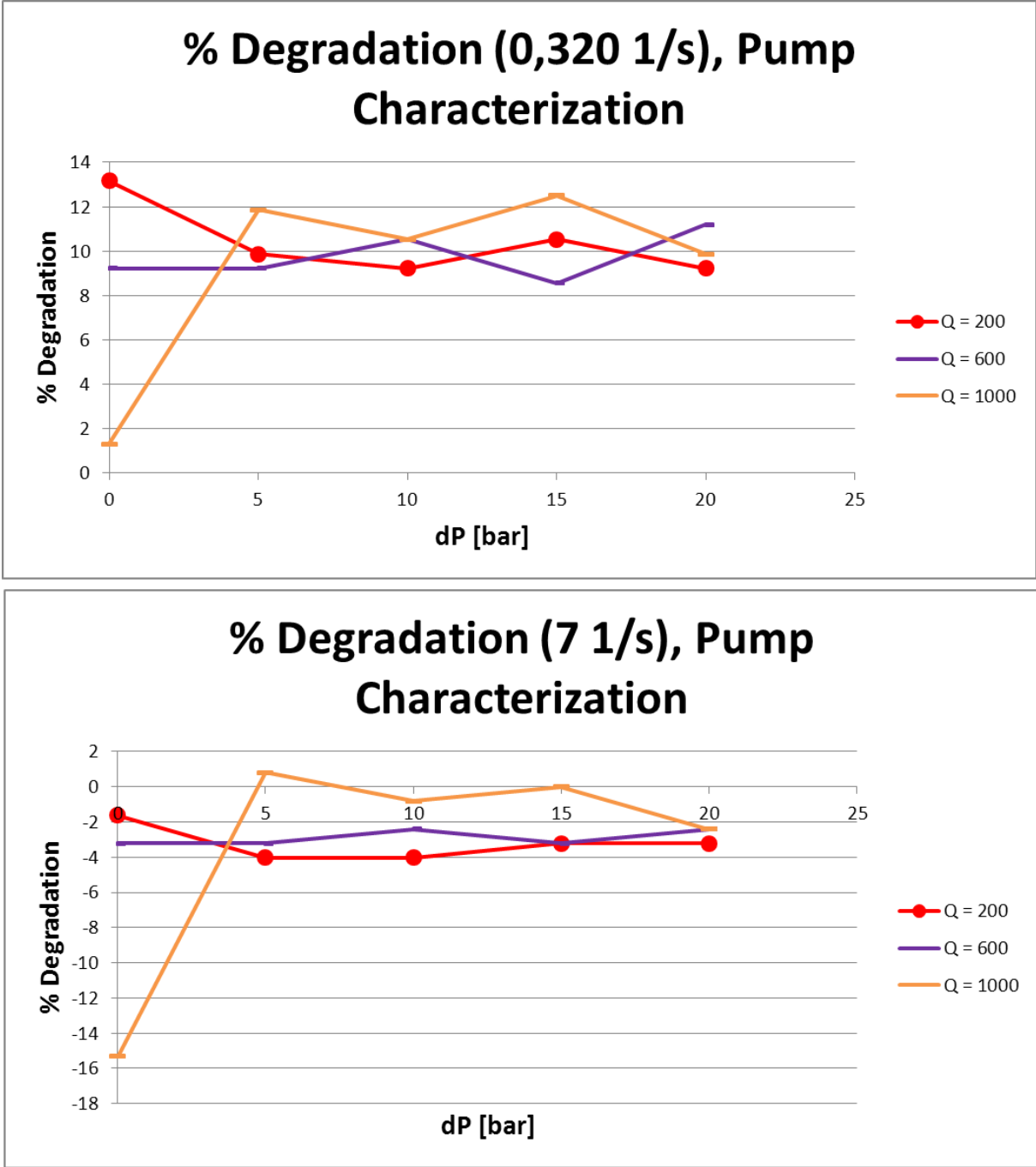
Figure 5-6: % degradation plotted as a function of dP at two different shear rates

The % viscosity degradation was calculated at a shear rate of 0.302 s^{-1} and 7.070 s^{-1}. As can be seen in the graph, % degradation remained nearly constant for every flow rates. Most

degradation of the solution occurred at Q = 200 l/h, 0 bar and at a shear rate of 0.317 s^{-1}, in which 13% degradation occurred. However, uncertainties in the viscosity measurements at low shear rates has to be accounted for [54]. It is very normal that the viscosity of the samples differ at low shear rates, even if the different samples have the same viscosity. It was seen that the viscosity for all the samples were almost identical as the tank solution in the previous graphs, besides for the samples taken at high pressure drop. The lower graph shows % degradation calculated at a higher shear rate. As can be seen in this graph, there are hardly any % degradation of the different samples, because at this shear rate, the viscosity is stabilized, and remains constant throughout all the samples, except for the samples taken at high pressure drop. There is a big difference in % degradation calculated at the two different shear rates. At the low shear rate, the degradation is in average 10%, while at the higher shear rate, the degradation is hardly 1 % in average. Figure 5-6 supports the conclusion withdrawn from figure 5-5, which was that degradation only occurs at very low shear rates, and that the viscosity of the solution stabilizes as the shear rate increases.

5.2.2 Second part - Cone sizes

The methodologies for this test program are to be found in chapter 4.2.4.2.

In this test, 5 cones with different cross sectional area were tested at different flow rates. The pressure drop for each cone and at its corresponding flow rate is given in table 5-1 below.

Q (l/h)	dP (bar) 6 mm	dP (bar) 8 mm	dP (bar) 10 mm	dP (bar) 12 mm	dP (bar) 15 mm
200	1.79	0.41	0.21	0.12	0.1
400	4.24	0.92	0.4	0.19	0.13
600	7.47	1.59	0.64	0.27	0.18
800	11.4	2.42	0.91	0.38	0.22
1000	16.27	3.24	1.18	0.48	0.28

Table 5-1: Pressure drop for each cone at its corresponding flow rate

As can be seen from the table, the 6 mm cone gave the highest pressure drop, and the 15 mm cone gave the least pressure drop, as expected. By adjusting the cross sectional area, the pressure drop can be regulated, which is one of the benefits of the Shark.

Results for the tests with different cone sizes are illustrated in figure 5-7 below. The figure is plots of viscosity as a function of shear rate for all the different coil sizes, and at different flow rates.
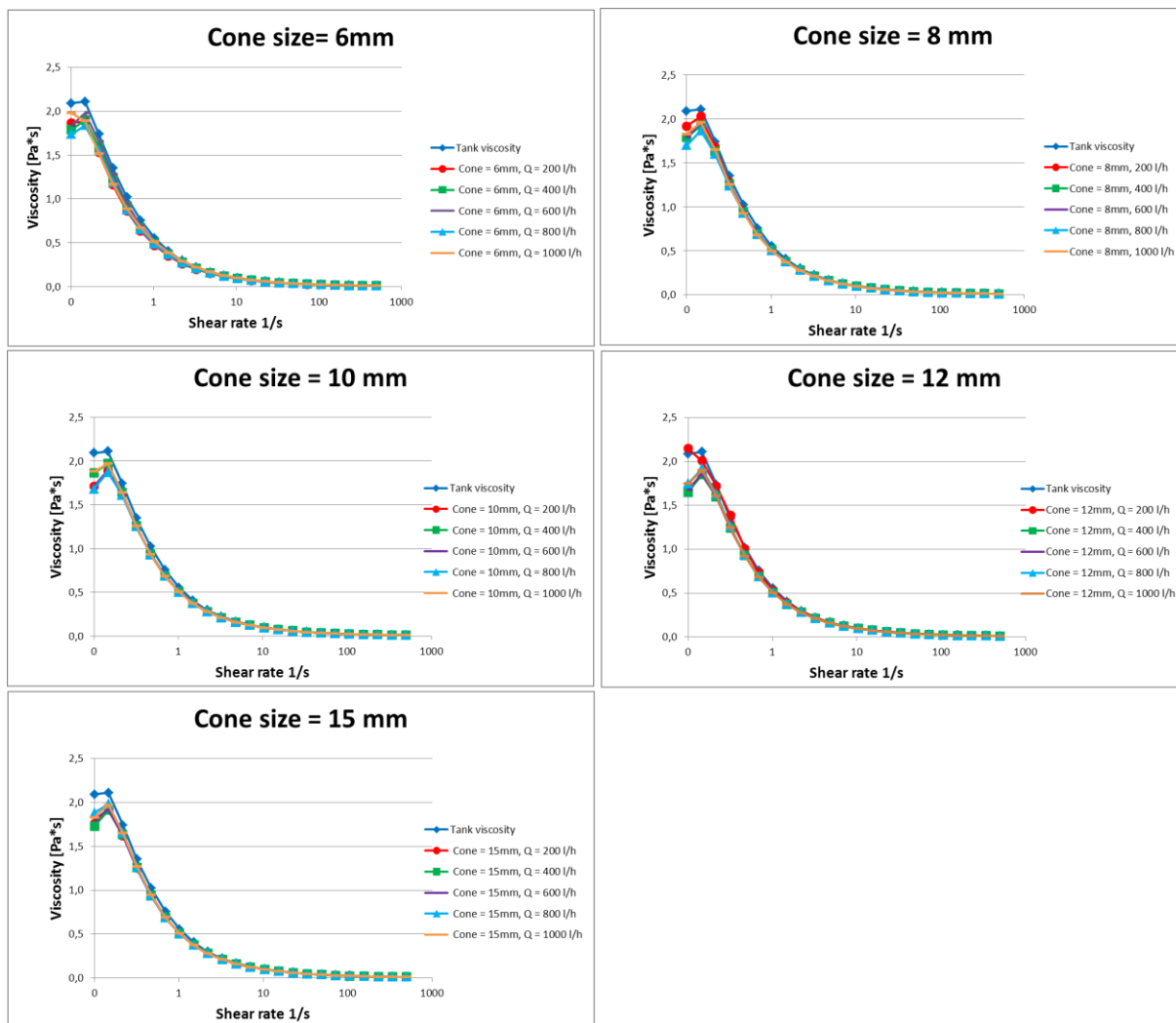
Figure 5-7: Viscosity as a function of shear rate at different flow rates

With reference to the figure above and figure 5-8, the same trends as for the pump characterization was observed in the tests with cones of different cross sectional area. The viscosity of the different samples from cone tests was almost the same as the tank solution viscosity at all shear rates. It is only at low shear rates $(0.1 – 0.3 \ s^{-1})$ the viscosity of the samples differ from the tank solution which is non–degraded. As the shear rate increases, the viscosity of all the samples approximates the same the viscosity of the non-degraded solution. This can be seen in figure 5-7 above, where the dark blue line is tank viscosity (non-degraded), and the other lines are the samples from the cone testing at different flow rates.

Further, it can be seen that all the flow rates gave almost the same viscosity of the solution. There is no big difference in viscosity between the different cones and different flow rates. It was assumed that most degradation would occur in the 6 mm cone, and the least degradation in the 15 mm cone. But, as can be seen in the figure, both cones gave the same viscosity of the solution, there is no big difference. It was especially thought that the 6 mm coil would degrade the solution to a much greater extent than what it actually did, due to the high pressure drop (16 bar). However, almost no degradation occurred. This can also be seen in figure 5-8 below, which shows % degradation as a function of flow rate.

% Degradation (0,320 1/s), Cones

% Degradation (7 1/s), Cones
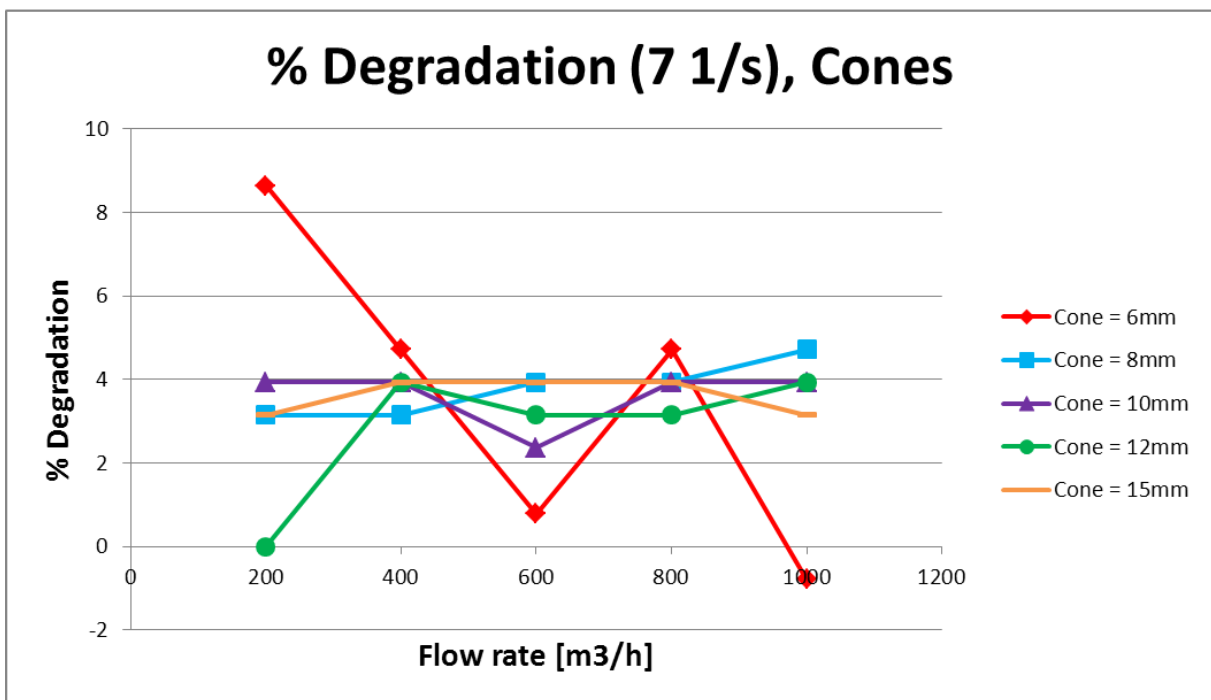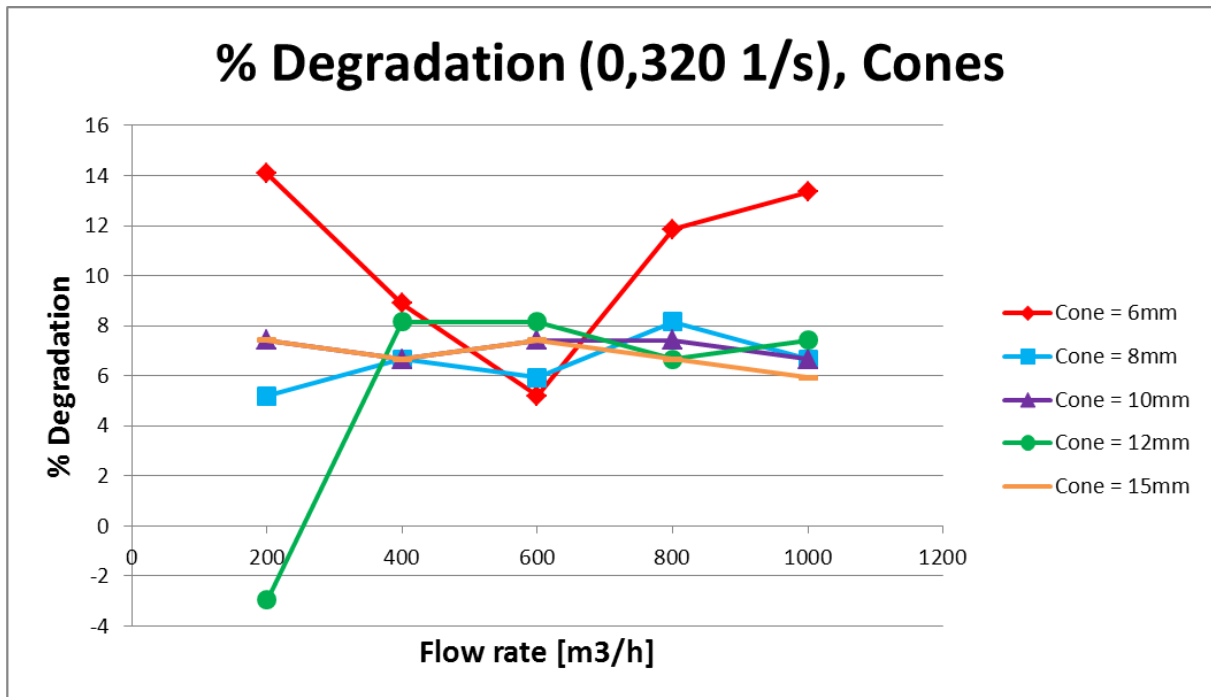
Figure 5-8: % degradation with cones as a function of flow rate and at two different shear rates

Even though the cones did not degrade the polymer solution to a great extent, % degradation was calculated on the same basis as for the pump characterization, and is described in chapter 4.2.5.3.

As can be seen in figure 5-8, upper graph, the % degradation remained almost constant throughout the different tests, with some aberration, especially with the 6 and 12 mm cone (red and green lines), and at flow rate 200, 800 and 1000 l/h respectively. This aberration is due to the fact that there are uncertainties in the measurements at such low shear rates, and the

lower the shear rate, the larger is the uncertainties. However, as can be seen, there is little degradation, even at this shear rate, for all the different coils, and at all the different flow rates.

The % degradation at higher shear rate is also constant throughout the different tests. This can be seen in figure 5-8, bottom graph. However, there are some aberrations, especially for the 6 mm cone (red line) at 200, 400 and 600 l/h. Further, the % degradation is much smaller at this shear rate than the low shear rate. For the low shear rate, the degradation is in average 8%, while at this shear rate, the degradation is in average 4%. This can also be seen in figure 5-7, where there is a small difference in the viscosity at the lowest shear rate (0.1 s^{-1}), and at higher shear rates, all the lines lie very close to each other, and to the non-degraded solution.

Even though the pump was used in these tests, the % degradation is smaller than for the pump alone. Again, the reason why, is because of the uncertainties in viscosity at low shear rates.

From these tests, it was seen that almost no degradation occurred in the cones. This is also illustrated in figure 5-9 below, which shows the normalized viscosity as a function of the calculated shear rates in the different coils and at different flow rates. Normalized viscosity and calculated shear rate is described in chapter 4.2.5.3, in addition to the equations used for the calculations.
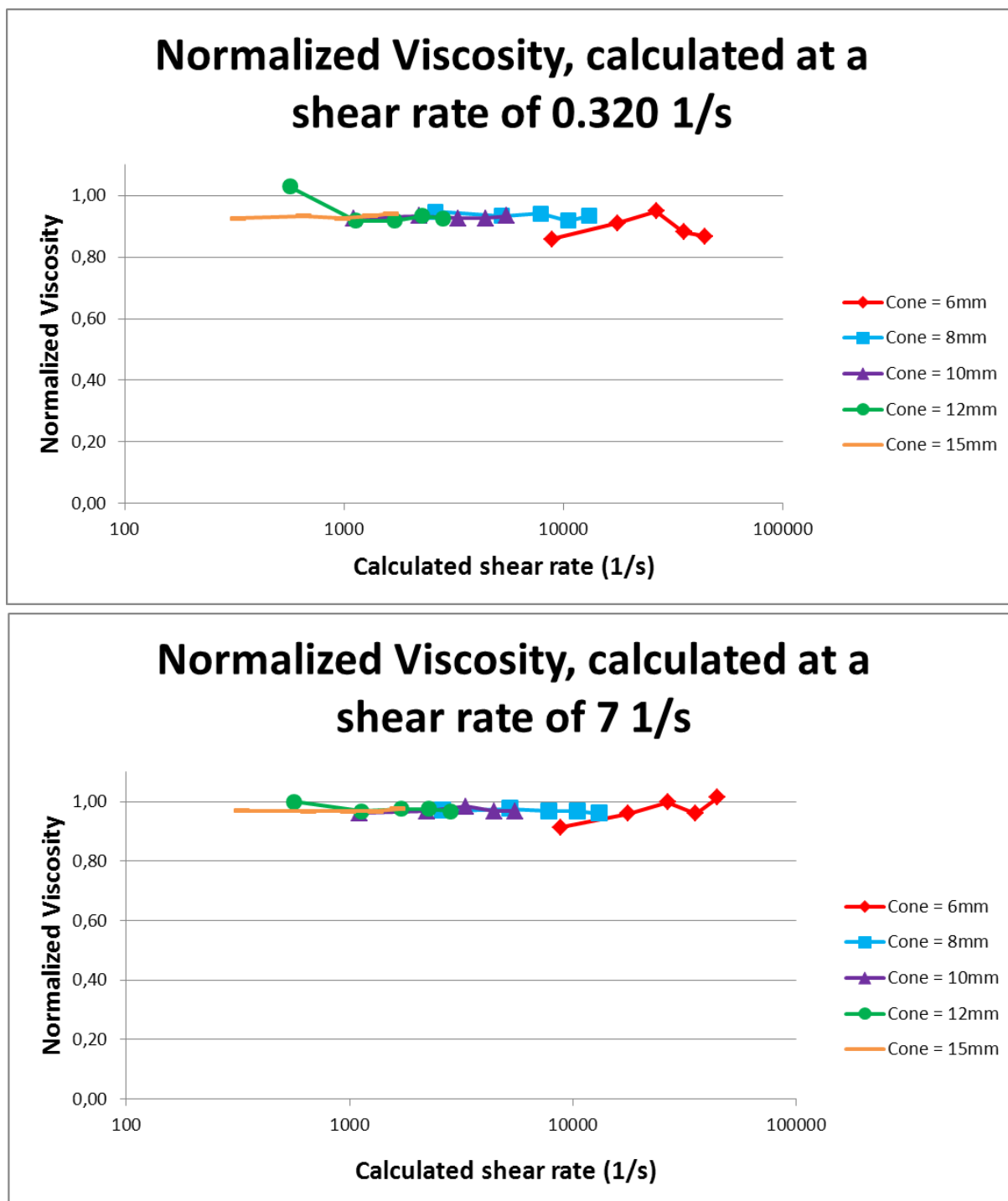
Figure 5-9: Normalized viscosity as a function of calculated shear rate for each cone

As noted, normalized viscosity at 1 means that no degradation have occurred, while a normalized viscosity of 0 means that the solution is fully degraded [54]. From the curves, it is clear that the solution did not degrade much in the cones, because the normalized viscosity is between 0.9-1 in all the samples, and at both shear rates. The reason why degradation did not occur is because of the minimized shear in the cones. The polymer used does not start to degrade before the shear rate is 18000 s^{-1} in salt water [54], this value is called critical shear rate. But due to the fact that these tests were performed with fresh water, an even higher critical shear rate can be expected, because polymers are more readily broken down in water

containing ions. From the calculation of the shear rates in the coils and at different flow rates, it is clear that the shear rates in the coils are too low to initiate degradation of the polymer solution. There are only in the 6mm coil, and at very high flow rate, the shear rate equals or is bigger then the critical shear rate of 18000 s^{-1}.

By using a cone with smaller diameter, or a higher flow rate, degradation would most probably occur in the cones.

5.2.3   Third part – Standard Valve Characterization

The methodologies for this test part are described in chapter 4.2.4.3.

A standard valve was tested on Q = 400 l/h and at pressure drop of 0, 5, 10, 15 and 20 bar, to see if and how much a standard valve degraded the polymer solution. The results are given in figure 5-10 below.
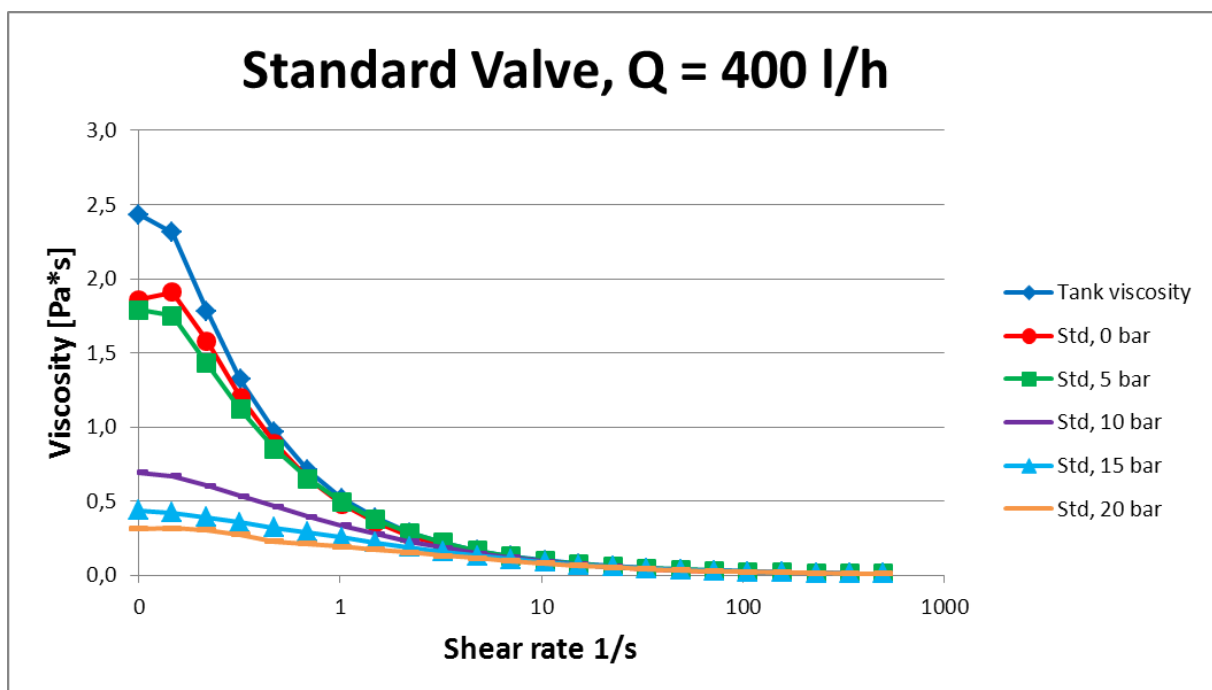
Figure 5-10: Viscosity as a function of shear rate

From the graph above, with the standard valve, severe degradation of the solution occurred, especially at 15 and 20 bars. At low dP, like 0 and 5 bar, there is degradation, but not as much as with higher dP. At these dP, the viscosity of the solution approximated the non-degraded solution at a shear rate of 0.3 s^{-1}, while for the higher dP, the viscosity did approximate the non-degraded solution at a shear rate of 3 s^{-1}. This clearly demonstrates that the standard valve did degrade the polymer solution, this can also be seen in figure 5-11 below, which is the plot of % degradation of the solution. The calculation procedure is described in chapter 4.2.5.2.
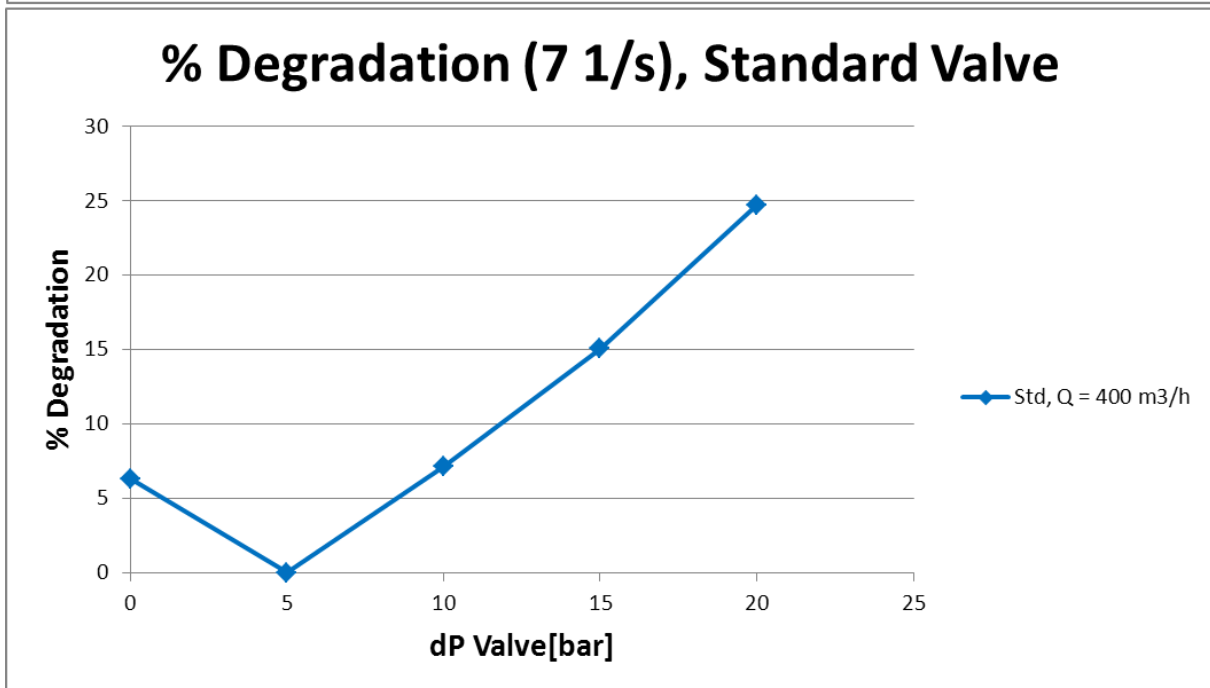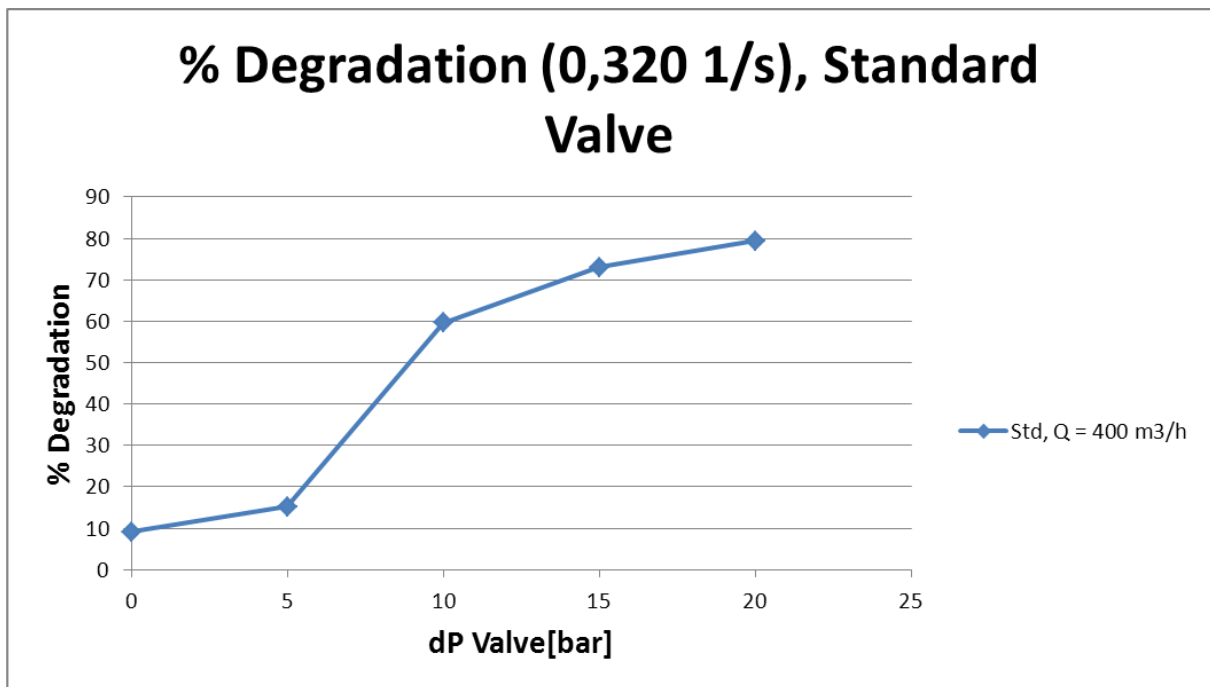
Figure 5-11: % degradation in the standard valve at two different shear rates

From the curves above, it can be seen that the degradation is not constant as it was for the coils. Here, the % degradation increases as the pressure drop increases, which clearly demonstrates the negative effect the standard valve has on polymer solutions.

The degradation is higher at the lowest shear rate, which is illustrated in the former curve. At a dP of 20 bar, the degradation is 80%, while at low dP it is 15 %. Even at zero dP, the degradation is 10%, which means that the valve by its self, with no pressure drop, contributes to degradation of the solution. At higher shear rate, the % degradation is minimized, which is illustrated in the latter curve. At most, the solution degraded 25% compared to the non-

degraded solution at this shear rate and at a dP of 20 bars. The reason why is because at higher shear rates, the viscosity of the samples are nearly the same as the tank viscosity, which is illustrated in figure 5-10. However, both of these curves shows the negative effect a standard valve has on polymer solution, because the degradation of the solution is much greater in this valve compared to the cones.

To demonstrate the positive effect the cones had on degradation of polymer, the standard valve was tested at the same conditions as the 8 mm cone + coil, and the results were compared. This is described in the next sub chapter.

5.2.4 Fourth part – Coil and Standard Valve
The methodologies for this test part are to be found in chapter 4.2.4.4.

In this test part, the 8 mm coil and a standard valve was tested and compared. The 8 mm cone was chosen and tested alone and with a 8 mm coil. The pressure drop for the cone alone, coil and the standard valve for its corresponding flow rates is listed in table 5-2 below. The standard valve was tested at the exact same pressure drop as the coil, such that the results could be compared.

Q (l/h)	dP (bar) cone	dP (bar) coil	dP (bar) std valve
200	0.43	1.99	1.99
400	0.88	4.08	4.08
600	1.50	6.6	6.6
800	2.40	9.13	9.13
1000	3.40	12.6	12.6

Table 5-2: Pressure drop for each coil at its corresponding flow rate

The new results for 8 mm cone were identical to the results of the previous testing of this cone size, so the only results given here are for the 8 mm coil and the standard valve. Testing of 8 mm cone alone was done solely to see if the new tests gave the same results as the previous tests. The purpose of these tests was to demonstrate that the coil does not contribute to more degradation than the cone alone, and to compare the degradation of the coil with a standard valve, tested at the exact same conditions. The results for 8 mm coil and standard valve is given below in figure 5-12.
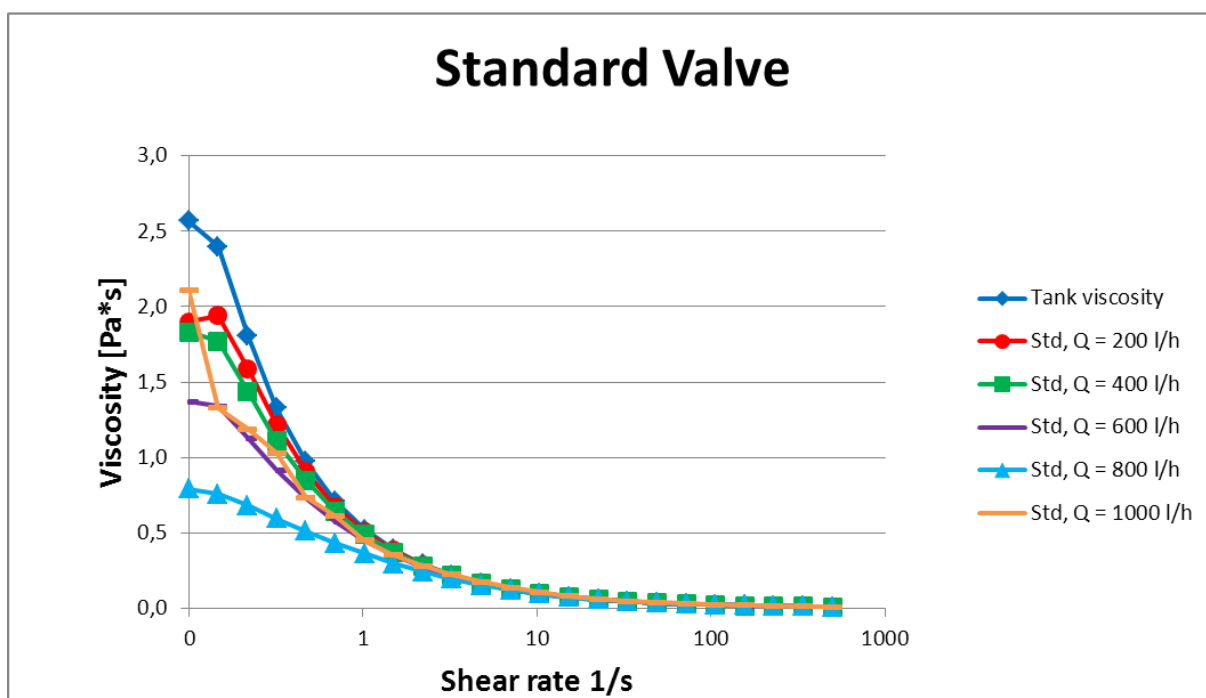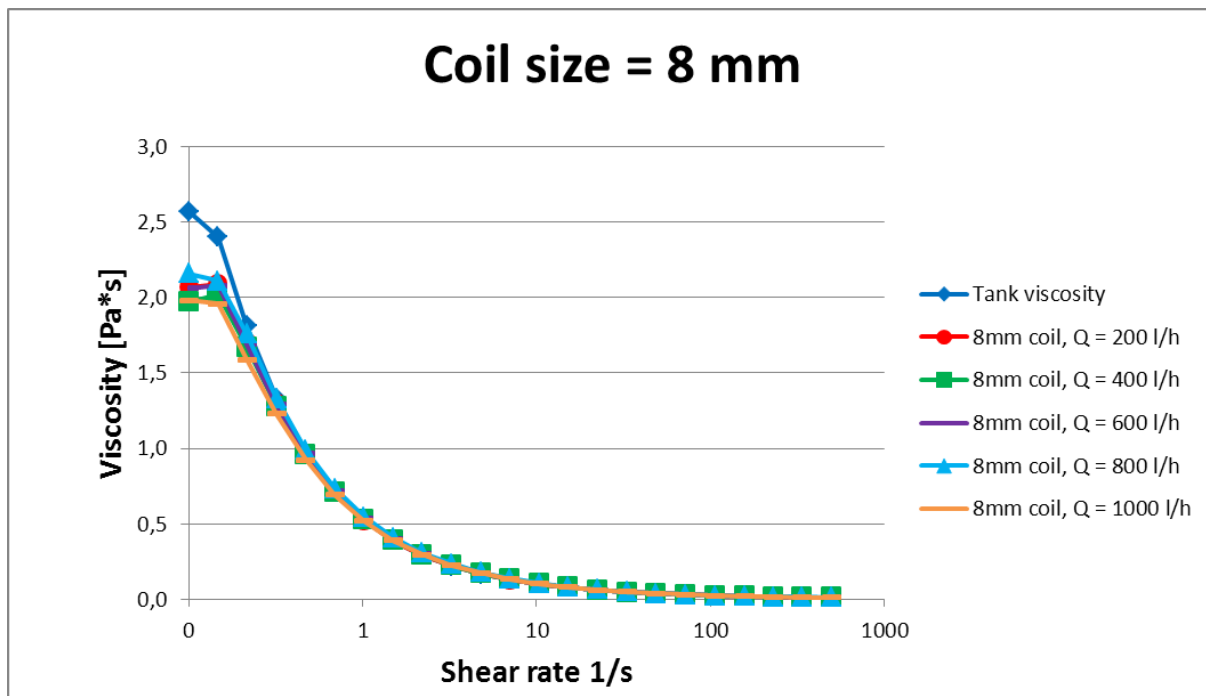
Figure 5-12: Viscosity as a function of shear rate for the coil and Standard Valve

As can be seen from the graphs, the coil did not contribute to more degradation of the polymer solution, so this test clearly demonstrated the positive effect the coil has on polymer solutions, even though the pressure drop was increased from 3 bars with the cone to 12 bars with the coil, at the same flow rate. Longer length increases the pressure drop, if the diameter is the same. Larger diameter and shorter length will decrease the pressure drop, while smaller diameter and longer length will increase the pressure drop. It was however not expected more degradation with the coil than with only the cone, because the pressure drop is reduced over a longer length. This was found to be true. The viscosity of the different samples with the coil

had almost the same viscosity as the non-degraded solution (dark blue line), with the only difference in viscosity is at lowest shear rates (0.1-0.3 s^{-1}). However, it can be seen that the standard valve, which was tested at the exact same flow rates with its corresponding pressure drop, did contribute to much more degradation of the solution. Here, the viscosity of the samples differs from the non-degraded solution at shear rates ranging from 0.1-3 s^{-1}, especially at 800 l/h.

The results are even clearer in figure 5-13 below, where % degradation for both the coil and the standard valve is plotted as a function of pressure drop, and at the two different shear rates. Calculation procedure is to be found in chapter 4.2.5.2.
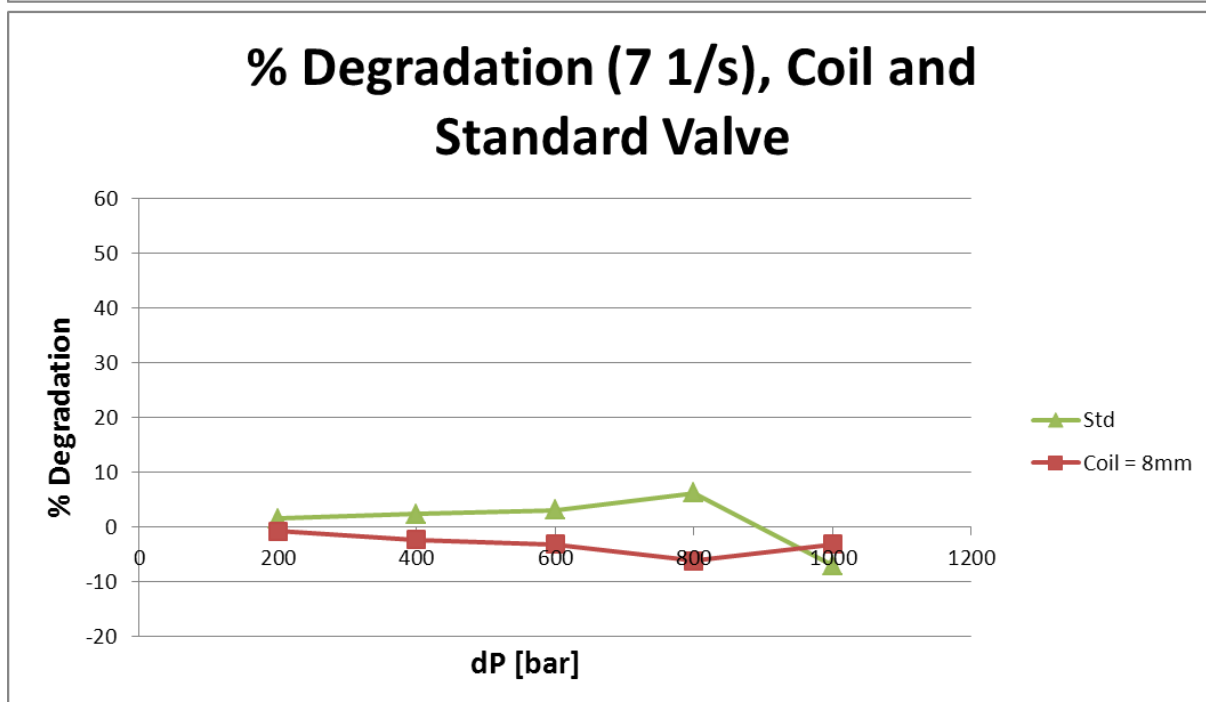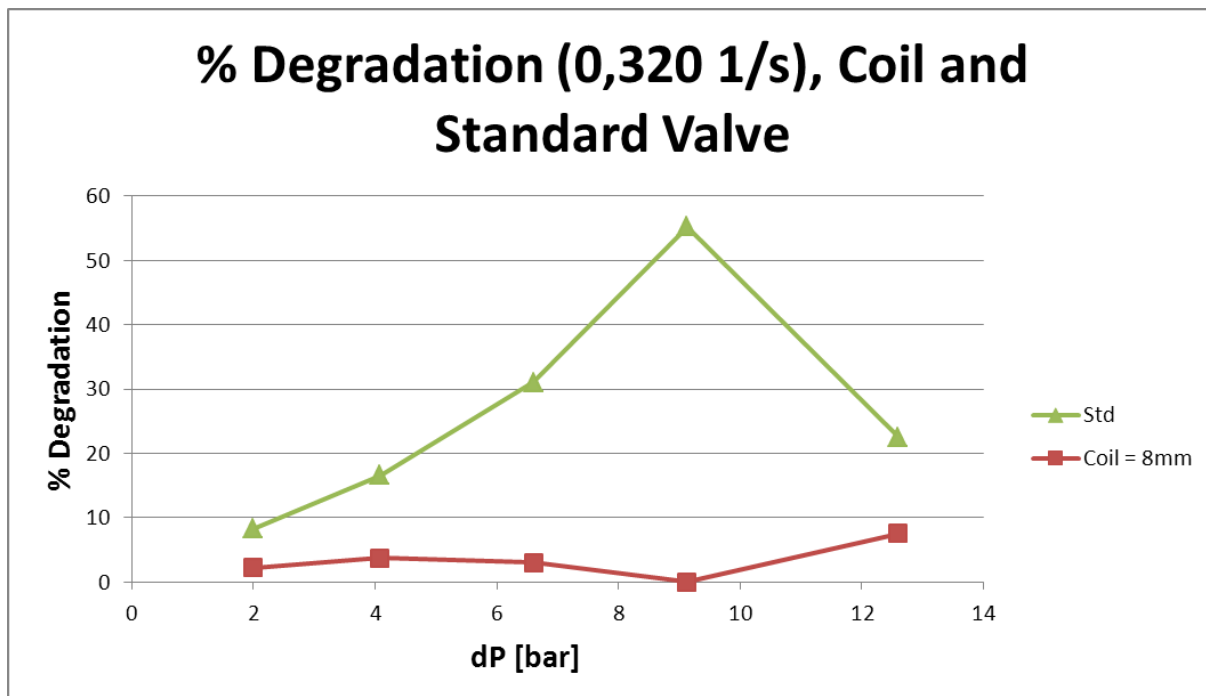
Figure 5-13: % degradation for both the spiral and the standard valve, as a function of pressure drop

Here, the degradation by the standard valve is clearly higher than for the coil at both shear rates. % degradation for the coil is nearly constant at all pressure drops, while for the standard valve, it varies according to pressure drop, with most degradation at a dP of 9.13 bar (800 l/h), with over 50% degradation, at the lowest shear rate. The least degradation occurred at a pressure drop of 1.99 bar (200 l/h), here only 10 % degradation. However, the coil did only give 2% degradation at the same pressure drop, and flow rate. The coil with a pressure drop of 12.6 bars did give the same % degradation as the standard valve at 1.99 bars. Again, the same trends which have been discussed and observed in the other tests can be seen here. At higher shear rate, the % degradation is much smaller, due to the fact that the viscosity of the

degraded samples approximates the viscosity on the non-degraded sample at higher shear rates. However, both curves above shows that the coils had in average 0% degradation, while the degradation increased as a function of pressure with the standard valve. This trend was not to be seen with the spiral.

This test confirmed the assumptions made, that the coil is very beneficial with regards to polymer degradation, due to the fact that the coil did not have a shear rate high enough to degrade the solution. The standard valve however have a shear rate which is larger than the critical shear rate, which results in severe degradation of the solution, even at low pressure drops.

5.2.5 Fifth part – Standard Valve and Typhoon Valve
The methodologies for this part are described in chapter 4.2.4.5.

This part comprises results from the tests with the Typhoon valve and the standard valve, tested at the exact same flow rates, with its corresponding pressure drop. The pressure drop for each flow rate is given in table 5-3 below.

Q (l/h)	dP (bar) Typhoon Valve	dP (bar) Standard Valve
200	0.65	0.65
400	1.61	1.61
600	3.10	3.10
800	5.21	5.21
1000	8.17	8.17

Table 5-3: Pressure drop for Typhoon and Standard valve at its corresponding flow rate

The results are illustrated in figure 5-14 below, which shows viscosity as a function of shear rate for both valves.
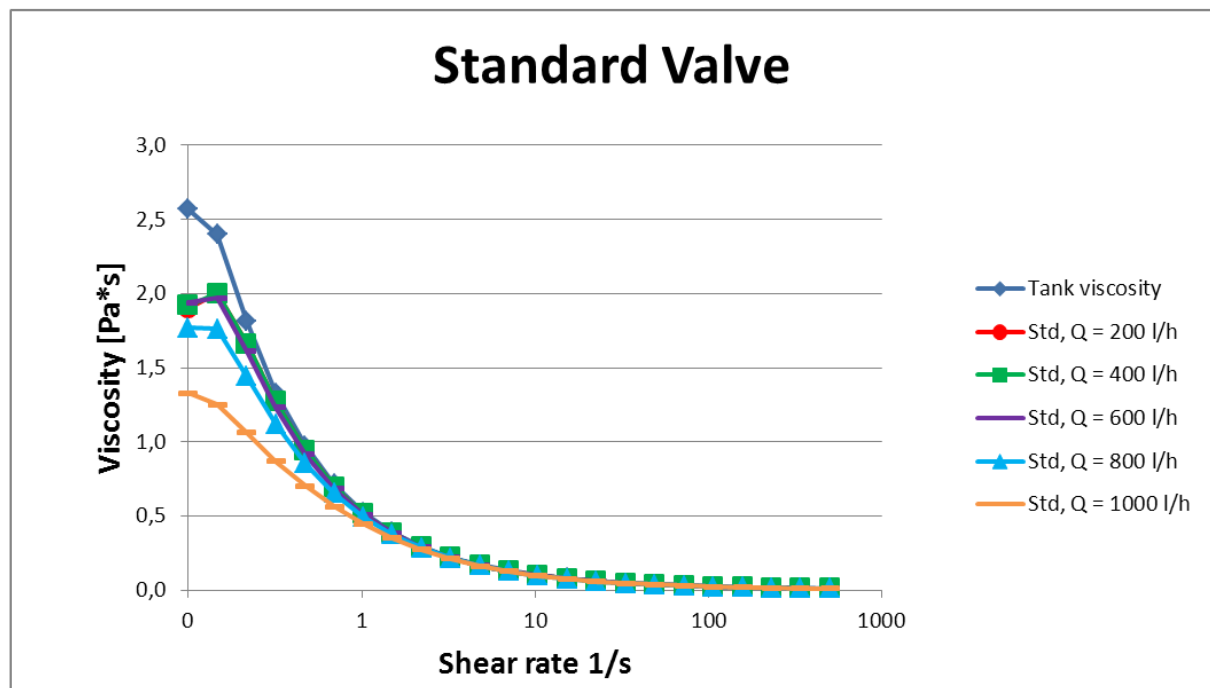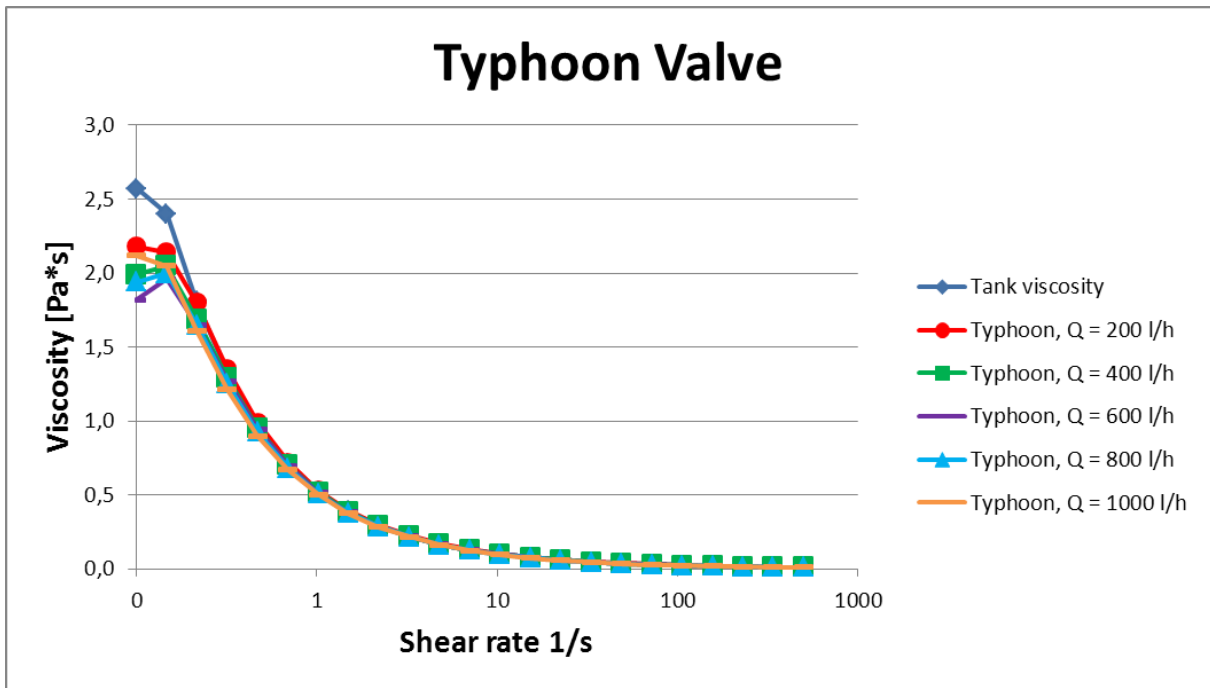
Figure 5-14: Viscosity as a function of shear rate for Typhoon and Standard Valve

From the graphs above, the same trends observed with the coils and spiral could be observed for the Typhoon Valve. The Typhoon Valve did not contribute to mechanical degradation of the solution, expect at very low shear rates (0.1 – 0.3 s^{-1}). By looking at the graph for the standard valve, it is clear that this valve contributes to mechanical degradation of the solution to a greater extent than the Typhoon Valve, especially at high flow rate due to greater pressure drop (8.17 bars). Even at low flow rates, there is degradation of the solution, not that much at 200 l/h, but with increasing flow rate and pressure drop, the degradation also increased. This is also illustrated in figure 5-15 below, which shows % degradation of the

solution as a function of pressure drop for both valves, and at the two different shear rates. Calculation procedure is to be found in chapter 4.2.5.2.
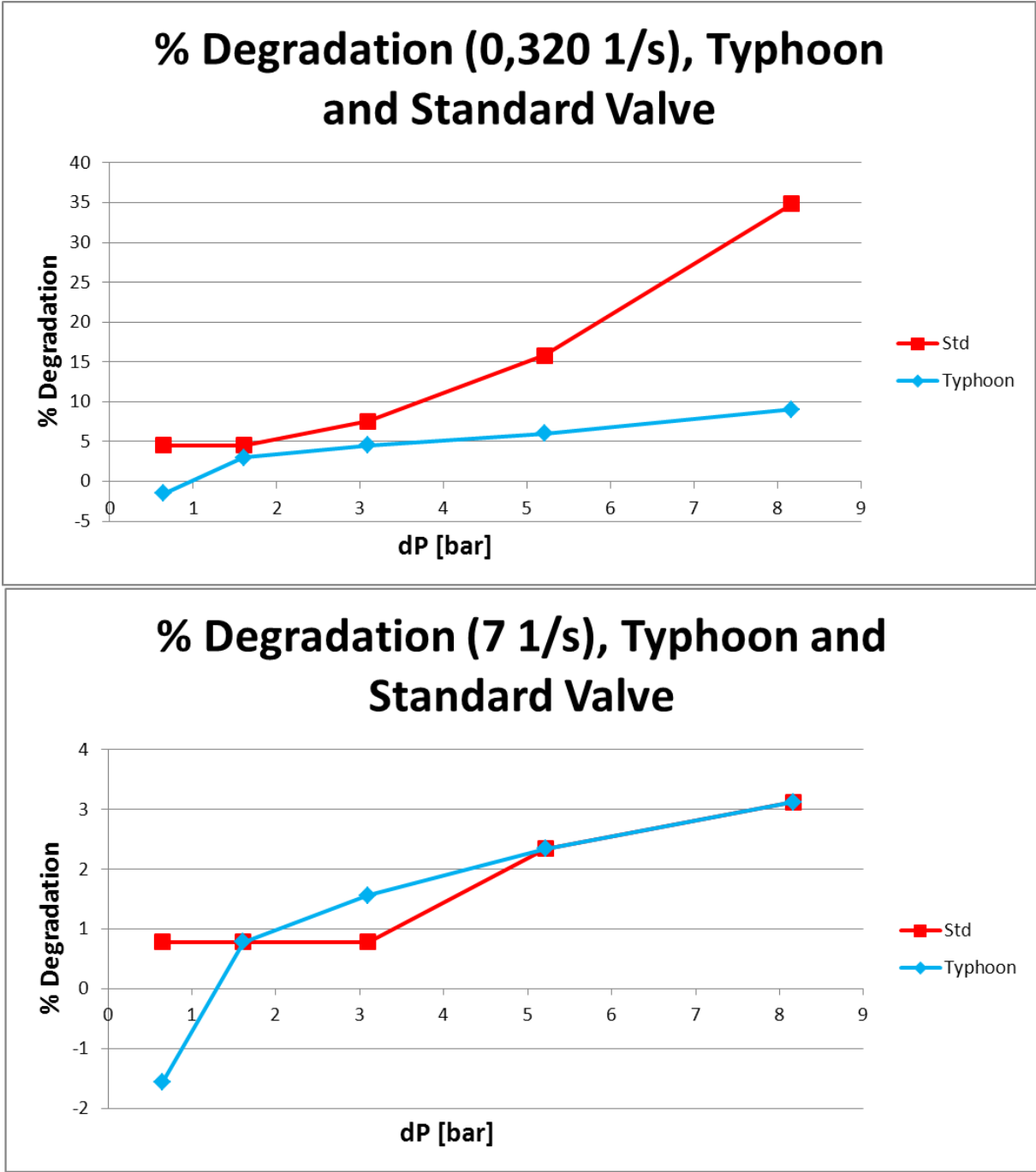
Figure 5-15:% degradation for both valves, as a function of pressure drop

This figure clearly demonstrates the more negative effect of the standard valve compared to Typhoon Valve on mechanical degradation at the low shear rate. As the pressure drop increases, the degradation also increases, especially for standard Valve. At a pressure drop of 8 bars, the standard valve contributes to 35% degradation, while the Typhoon Valve only contributes to 10% degradation. The reason why the difference between the valves is small at low flow rates is because of the small pressure drop. At low pressure drops, the degradation is minimal for both valves, and it is not until the pressure drop increases, the amount of

degradation between the valves really differ. It is to believe that at even higher pressure drop, the standard valve would contribute to even more degradation, compared to the Typhoon Valve. As noted in chapter 4.2.4.3, at a flow rate of 400 l/h, and pressure drop of 20 bars, the degradation by the standard valve is 80 %. However, at the high shear rate, the % degradation for both valves is approximately the same, especially at high pressure drops. The reason might be because the pressure drop in the valves is so small, such that the effect of degradation is minimized. Because of low pressure drop, the solution will not degrade so much, such that at a high shear rate, the viscosity of the samples approximated the viscosity of the non-degraded sample. At higher pressure drop, the solution would have been more degraded, with a greater loss in viscosity. Hence, the viscosity of the degraded sample would approximate the viscosity of the non-degraded sample at a much higher shear rate, and larger % degradation would have been observed at a shear rate of 7 s^{-1}.

However, from this test, it is to believe that a Typhoon configuration would be beneficial with respect to mechanical degradation. The trend for this valve is the same as for the coils, which also have been proven to minimize mechanical degradation of the solution, compared to a standard valve. Further, it is to believe that a higher pressure drop would have resulted in more degradation in the standard valve compared to the Typhoon Valve. This is also documented in chapter 4.2.4.3 where a standard valve was characterized. It was seen that high dP gave severe degradation of the solution. Also in figure 5-15 above, at low shear rate, the increase in % degradation for the standard valve is much more rapid than for the Typhoon Valve.

At the higher shear rate the degradation was approximately the same for both valves. However, the degradation is so small, that it is almost negligible, which means that the solution was not that degraded in the valves, due to small pressure drop. If the valves had degraded the solution to a large extent, the viscosity would have been much smaller at all shear rates, not just at the low shear rates. Again, difference in viscosity at low shear rates is due to uncertainties and sound at these low shear rates.

5.2.6 Comparison

From state of the art in polymer injection and Vladimirs bachelor thesis, it was thought that the coils could have a very positive effect on mechanical degradation of polymers. From the invention by Dyck and Ken Krewulak (chapter 2.7.1 and 2.7.2) is has been seen that coils and pipes are very beneficial when it comes to mechanical degradation of polymer solutions. Vladimirs bachelor thesis also showed that the coils have a positive effect on coalescence and droplet break-up of oil in water emulsions. The assumption that the coils also would have a positive effect on mechanical degradation of polymers was verified in this thesis. From the testing of all the different cone sizes, and the coil, almost no degradation occurred, due to the fact that the shear rates in the cones and coils were not high enough to initiate shear degradation. This has proven that, even though the pressure drop across the coil is high, no degradation occurs because the pressure drop is reduced over a longer length than in a conventional valve, which results in lower shear rates, hence lower shear degradation. That is also the reason why the Typhoon Valve has shown to have a positive effect on mechanical

degradation. The pressure drop is gradually reduced in a bigger volume, and not over the cage as in a standard valve, which means that the energy dissipation unit is decreased, and hence less shear forces and shear degradation of the solution.

5.2.7 Benefits by using low shear technologies

Today, the solution to the problem with polymer degradation is often solved by adding more polymers to the injection water, which have a negative effect, with respect to the environment, as well as the economy. In Norway, polymers are regarded as red chemicals, and can not be discharged directly to the sea. It has to be separated from the produced water, which is a challenge, due to high viscosity. A method it so break the polymers, which will decrease the viscosity, hence, better and easier separation. However, the problem is breaking the polymer enough, to gain low enough viscosity for an easier separation. By using low shear technologies, such as the Shark and Typhoon Valve, less polymer has to be added to the injection water compared with conventional valves, to gain the same efficiency and viscosity. This will have a very positive effect on the separation process, the environment and the economy, as well as time saving.

6 CONCLUSION

The conclusions which are withdrawn from this experimental testing is divided into two sub chapters, one for the 2" Typhoon Valve tested in France, and one for the cones, coil and Typhoon configuration tested at Varhaug. In addition, a third sub chapter contains suggestions for further testing and work.

6.1 Typhoon Valve tested in France - Pre Project

The pre-project did not give the positive results that were expected, and it was not seen any big difference in degradation between the Typhoon Valve and standard valve. The main conclusions withdrawn from the testing were:

- At high pressures (30 – 40 bars) both valves gave up to 70% degradation of polymer solution
- High flow rate and low pressure drop gave 10% less degradation with the Typhoon Valve, compared to a standard valve. 30% degradation (Typhoon) compared to 40 % degradation (Standard)
- At lower flow rates and higher pressure drop, no significant difference between the valves with regard to degradation of polymer, in fact, at these conditions, standard valve gave less degradation than the Typhoon Valve

It is believed that the disappointing results can be explained by the valve capacity. The internals in the valve were not optimized for these test conditions, nor the capacity. At high flow rates, the valve functioned much like a standard valve, which means that all the pressure was reduced over the cage, with not enough inlet momentum to create the beneficial vortex. This means that the low shear principles in the valve did not function properly.

6.2 Coils, Typhoon Configuration and Standard valve – Main Project

This testing which is part of the main project gave very positive results, even more than was expected for the cones and small scale Typhoon Valve. The main conclusions withdrawn from the testing of cone and coils were:

- Almost no degradation in the cones or the coil, even at the highest pressure drop and flow rate
- No more degradation with the coil compared to the cone, which means that longer length/spiral does not contribute to more degradation
    - ➢ The cones and coil gave approximately 0% degradation, while standard valve gave over 50
    - ➢ % degradation at some test conditions

- Not high enough shear rate created in the cones to initiate shear degradation of the polymer solution
  - Shear rates less that 18 000 s^{-1} in all the cones which is the critical shear rate for this polymer. This explains the reason for no observed degradation

The small scale Typhoon Valve did not give as positive results as the cones and coil, however, the results were promising compared to the standard valve. The main conclusions from the testing with small scale Typhoon Valve were:

- Less degradation than the standard valve at every flow rates and pressure drops
- Biggest difference in % degradation between the valves at high pressure drop
  - At 8 bars, Typhoon Valve gave 10% degradation, while Standard Valve gave 35% degradation
- At lower pressure drop, the difference was smaller in % degradation between the valves
  - At 3 bars, the Typhoon Valve gave 5% degradation, while the Standard Valve gave approximately 7.5% degradation

It is to believe that even higher pressure drops would be even more beneficial with the Typhoon Valve, compared to the Standard valve.

6.3 Viscosity measurements and calculations

This chapter summarizes the conclusions from viscosity analysis for both the pre-project and main project. The trend that was found during viscosity measurements and analysis was similar in both projects, and they were:

- Small differences in viscosity, if any at higher shear rates for both the cones, coil and Typhoon Valve
- Biggest difference in % degradation at low shear rate (0.320 s^{-1}) compared to higher shear rates (7 s^{-1})

The explanation for the differences in viscosity at low shear rate during viscosity measurements is large uncertainties at low shear rates (< 0.3 s^{-1}).

6.4 Suggestions for further work

6.4.1 Typhoon Valve – Pre – Project
Further work should and are planned to be conducted as part of the main project. Further suggestions and further tests with the 2" Typhoon Valve are:

- New testing with 2" Typhoon Valve, with optimized internals, to achieve optimized capacity
- New testing with 2" Typhoon Valve at higher flow rates, to se if these conditions reduces mechanical degradation to a greater extent than a Standard valve
- Take samples upstream the 2" Typhoon Valve in the test-loop in France, to see if other components contribute to mechanical degradation of the polymer solution

6.4.2 Cones and coils (the Shark)

Due to the very positive results from the testing, further tests are suggested. Further suggestions and the further tests planned to be conducted are:

- Construct cones/coils with small enough diameter to create higher shear forces
- New testing with cones at higher flow rates to increase the shear rate inside the cones, over the critical shear rate for the polymer, and compare to a standard valve, tested at the same conditions

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A APPENDIX – THEORY BACKGROUND

A.1 Project objectives

Typhonix and TOTAL E&P Norge have executed an R&D agreement on the subject of "Mechanical Degradation of EOR/IOR Polymers caused by Process Equipment". This agreement is based on a pre-project verification study supported by Petromaks (Project no: 220331/E30). The overall objective is to develop and design a process for low shear injection of polymer which reduces the mechanical degradation of the polymer and thereby reduces the loss of viscosity with 50% compared to the state of art [55]. The objective is to establish a good overview and understanding of the total system for preparation, transportation, injection and flow of polymer solution through the reservoir formation, and identify process equipment and other obstacles where mechanical degradation may occur. Polymers are susceptible to high shear forces, and due to high shear forces in traditionally valves, it is to believe that Typhoon valve will give less degradation of the polymer compared to the state of art technology. Other objectives will be to qualify and demonstrate the positive benefits the Typhoon Valve may have on polymer flooding. Due to less pressure drop in the valve and hence less shear, degradation of polymer may be reduced by use of the Typhoon Valve. Fluid flow samples before and after the device being tested at different flow rates, pressure drop and polymer concentrations will be taken. The samples will be subject to rheological analyses, and the viscosity of the sample before and after the device responsible for shear forces will be compared to identify and analyze the difference in loss of viscosity.

A.1.1 Detailed test objective

Objectives of the test besides the ones that are described under project objectives are:

2. Identify all process units and obstacles that cause degradation of polymer.
3. Optimize the geometry and design of the Typhoon® Valve for reduced mechanical degradation of polymer solutions. (As much as 50% of the loss of viscosity is caused by the shearing forces in the choke Ref.: SPE 135735).
4. Optimize the geometry and design of the Typhoon® Pump for reduces mechanical degradation of polymer solutions. (It is misconception in parts of the industry that certain pumps do not degrade polymers).
5. Optimize or redesign other process units or obstacles that cause mechanical degradation (mixers, well stream entry or injection points).
6. Design a generic process system for injection of polymer solutions based on the new low shear technology.
7. Through experimental work, provide the industry with more reliable data on mechanical degradation of polymers in order to improve the dynamic simulation modeling of reservoir flooding operations.

In order to realize the planned innovation, it is essential to attack the obstacles causing the problem of mechanical degradation and to reduce the harmful effect where it occurs. The anticipated results of the project is a method of preparing and injections polymer solutions with a significantly higher viscosity than what is possible with the technology of today, and also anticipate experimental data on mechanical degradation of polymers in a format useful for improving the models of dynamic simulations of reservoir flooding. The synthetic polymer, hydrolyzed polyacrylamide, is categorized as a red chemical in Norwegian waters, and we expect that our planned innovation will reduce the consumption as well as the emissions of chemicals to the environment.

A.2   Background for the Typhoon Valve

The following sub chapters gives a fully review on the technology which are background for the development of the Typhoon Valve, as well as similar technologies and concept as the Typhoon Valve.

A.2.1   Choke modification done by Delft University of Technology

Experimental work has been carried out by Delft University of Technology in the Netherlands with focus on modified choke design, reduced oil droplet break-up under high water-cut production wells [34]. High energy dissipation in the choke due to pressure drop within the system leads to severe break-up of dispersed oil droplets. Previous experimental work has found that break-up is a result of the choke geometry, and modifications on the geometry may reduce droplet break-up. Results from the experimental work showed that it was possible to reduce droplet break-up by modification on the choke. Because energy dissipation rate in the choke is inverse proportional to the length, the bigger/longer the choke is, the less turbulence in the choke, hence droplet break-up.

Three model chokes were tested, an orifice, a small choke consisting of 7 parallel tubes and a larger choke consisting of 13 parallel tubes. These three chokes were tested with the same test parameters, the same flow rate and the same pressure drop across the chokes. The results were that the largest choke was superior, less droplet break-up occurred in this device. Some droplet break-up occurred in the small model choke, while severe break-up occurred in the circular orifice.

The 7-tube restrictor consisted of 7 parallel, smooth tubes. Each tube had a length of 50 mm and a diameter of 2.0 mm. The 13-tube restrictor was developed after the experiments with the 7-tube restrictor. Analysis of the 7-tube restrictor indicated that more tubes, and longer tube lengths would be advantageous with respect to droplet break-up. Figure A-1 below illustrates both the 7-tube restrictor and the 13-tube restrictor. The circular choke restrictor had a diameter of 5.5 mm and a thickness of 3.0 mm, with an internal diameter of 15.25 mm. With these sizes, this restrictor had a comparable flow-rate/pressure drop behavior as the 7-tube and 13-tube restrictors. The circular choke restrictor is a typical choke used in oil field practice, with a rather high turbulent intensity. The 7-tube and 13-tube restrictor had a

distribution of the pressure drop over a relatively large length, such that the prevailing pressure gradient and the turbulent intensity were lower than for the circular choke restrictor.
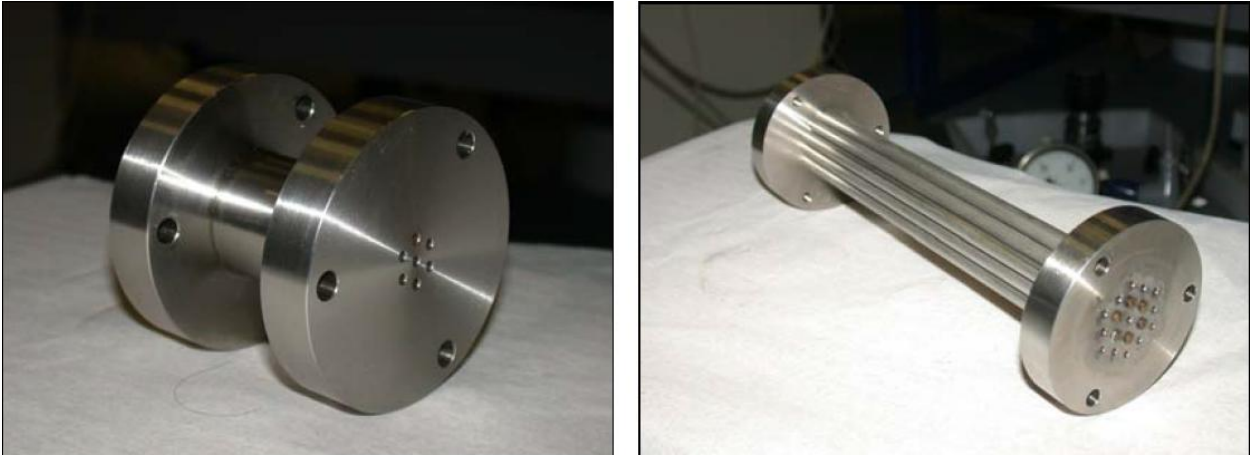
Figure A -1: Illustration of the 7-tube and 13-tube restrictor, respectively

In the experiments, the pressure drops for water flows of 20, 22.5, 25 and 27.5 l/min were measured. It was shown that circular 5.5 mm restriction had almost the same pressure drop/flow-rate as the 7-tube restrictor. However, the pressure drop was considerably lower for the 13-tube restrictor. The results for dv(50) for the different restrictions from the experiment are shown in figure A-2 below.
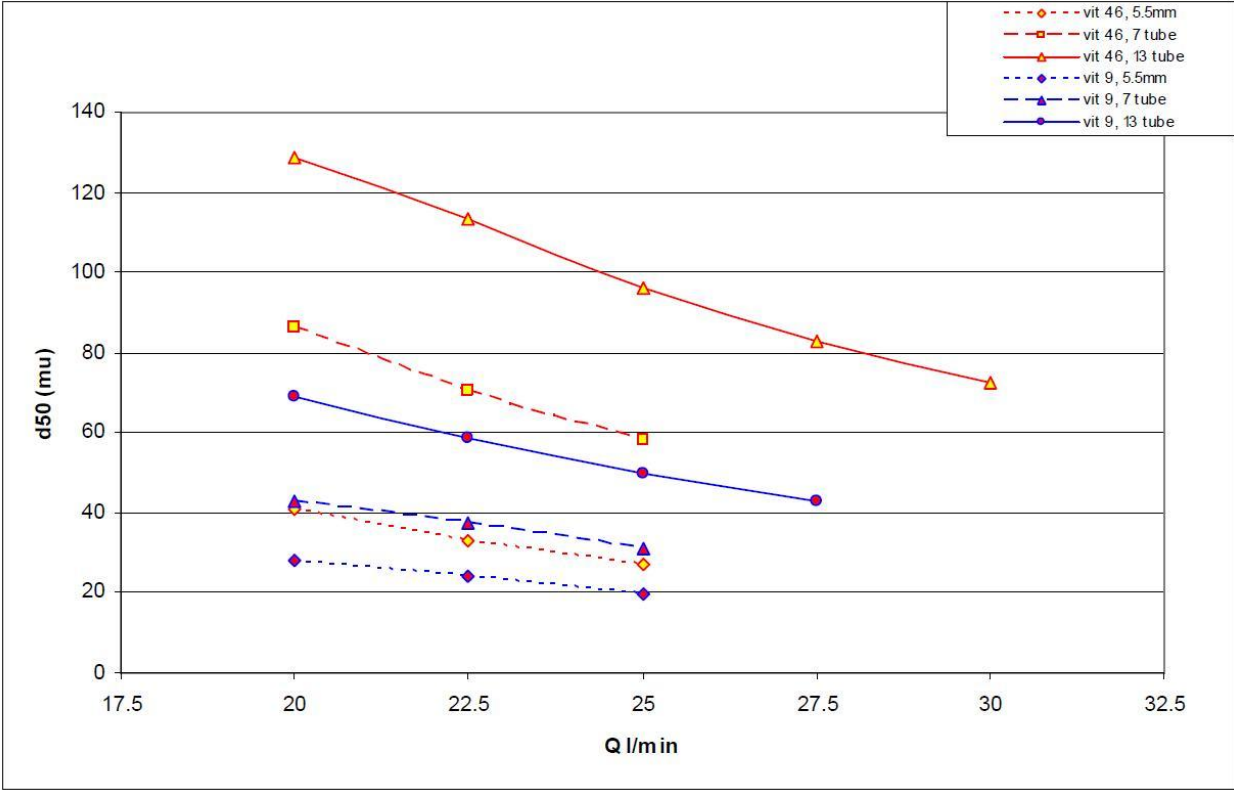
Figure A-2: Dv(50) as a function of flow rate for the three different restrictions

As can be seen from the figure, dv(50) was considerably larger for the 13-tube restriction than for the two other restrictions. This means that the increased length results in reduced turbulence, hence less droplet break-up.

A.2.2 *Cyclonic low shear valve testing done by Petrobras in Brazil*

Petrobras has tested a cyclonic low shear valve prototype at Petrobras Experimental Center (NUEX) in Aracaju/SE [35]. The valve can be used as a choke valve, as a valve between separation stages and for controlling the level of vessels.

The cyclonic low shear valve is a modified conventional globe valve, and the modified cyclonic valve has been tested and compared with a conventional globe valve. The purpose of the testing was to demonstrate the advantages of using a low shear cyclonic valve instead of a conventional valve in separation processes. The results from the tests showed that the cyclonic valve had a better performance compared with the conventional valve, and that the performance was a function of several parameters, like emulsion stability, water content free, and oil properties. An illustration of the cyclonic valve and the conventional globe valve is given in figure A-3 below.
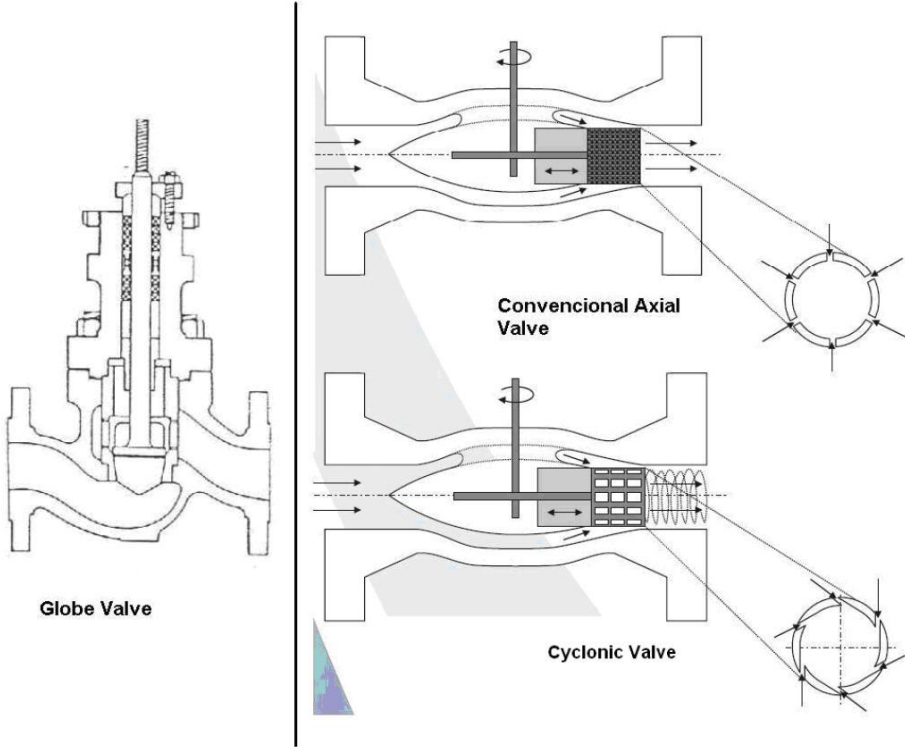
Figure A-3: An illustration of the cyclonic low shear valve and a conventional globe valve

The cyclonic concept is to give a rotational flow pattern downstream the valve, which reduce turbulence zones and increase droplet coalescence. The pressure drop in the orifice restriction is smaller than in conventional valves, which gives energy loss when generating the vortex downstream of the valve. This contributes to the cyclonic effect and droplet coalescence instead of droplet breakup. The cyclonic valve is illustrated in figure A-4 below.

Figure A-4: low shear cyclonic valve testet by Petrobras

The fluids that were used in the tests were saltwater and an oil blend, in order to achieve a value of 20 cP of oil viscosity. The flow rates were 30 m^3/h to 45 m^3/h, and the pressure drops were from 4 kgf/cm^2 to 10 kgf/cm^2. The results were that the cyclonic valve had superior performance compared to the globe valve. This indicates that the distribution of droplets generated by the cyclonic valve was reduced compared with the distribution generated by the globe valve. Also, as figure A-5 below illustrates, the water contains much less oil after separation with the use of the cyclonic low shear valve.

Figure A-5: Results from the testing at Petrobras

A.2.3   Separation system comprising a swirl valve

Twister has invented a low shear separation system which comprises of a swirl valve which receives and controls the flux of a fluid flow via the flow inlet and generates a swirling flow [31]. A separation chamber downstream the swirl valve receives the swirling flow, and comprises a first and second flow outlet. The first flow outlet receives an inner portion of the swirling flow, while the second flow outlet receives an outer portion of the swirling flow. The swirling flow has two advantages:

1) Regular velocity pattern which leads to less interfacial shear, less droplet break-up and larger droplets.
2) The concentration of droplets in the circumference of the flow area increases which means large number density, improved coalescence and larger droplets.

The swirl valve has a cage with tangential openings instead of radial openings which conventional valves have. The tangential openings makes a more regular swirl pattern, this introduces less shear forces and less droplet break-up and more coalescence than with conventional valves. Radial openings introduces higher shear forces, hence droplets break-up into smaller droplets. Figure A-6 below gives a schematic description of the embodiment [22].
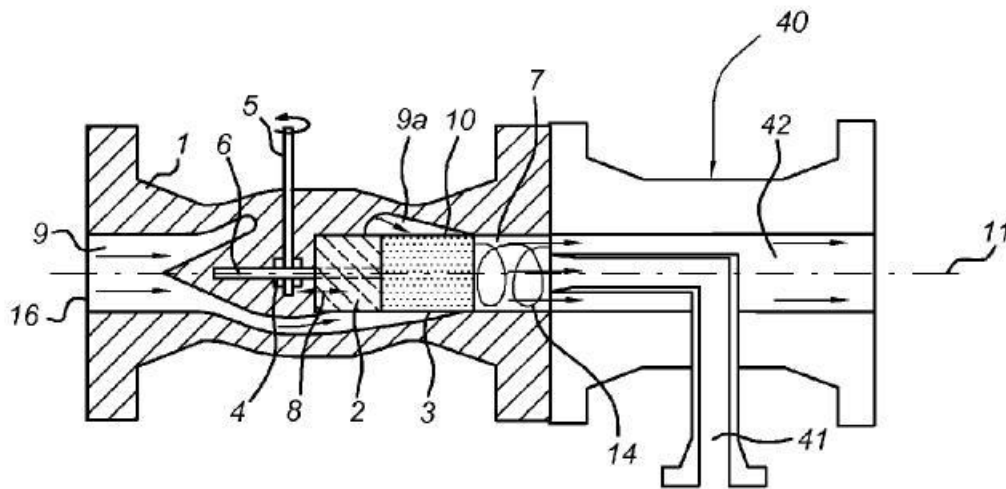
Figure A-6: Schematic drawing of the present embodiment

The separation system comprises a flow inlet (16) and a swirl valve. The swirl valve receives and controls the flux of the fluid flow form the flow inlet, in addition to generate a swirling flow which swirls about a central axis (11). A separation chamber (40) is positioned downstream the swirl valve, which receives the swirling flow from the swirl valve, and which comprises a first and second flow outlet (41, 42). The first outlet (41) receives an inner portion of the swirling flow, while the second outlet (42) receives the outer portion of the swirling flow. The swirling valves may be as shown in figure A-7 below.
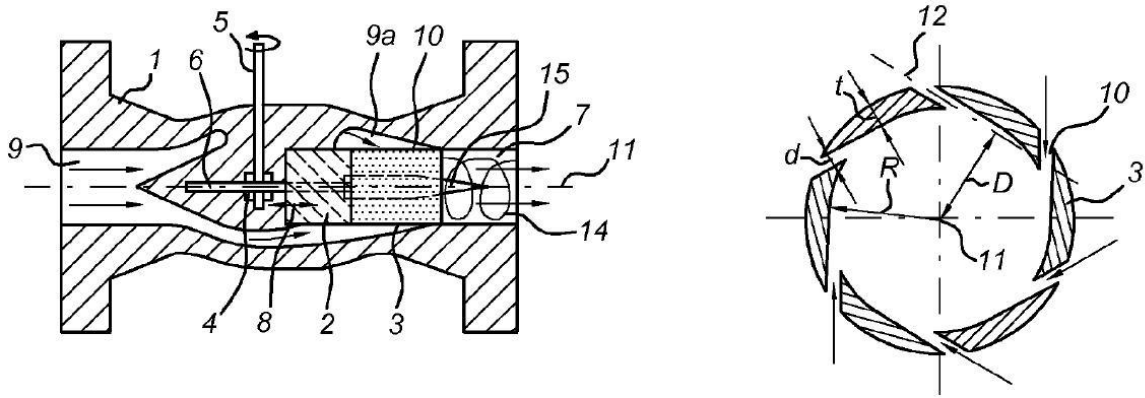
Figure A-7: Illustration of swirling valves in the present embodiment

The swirling motion is created by the available free pressure in the fluid. The first flow outlet receives a relatively small portion of the swirling flow, while the second outlet receives a relatively heavy portion of the swirling flow. This is due to swirling motions that makes the swirling flow to be forced to the outer periphery.

The separation chamber (40) is arranged to separate a two-phase fluid flow into a light and heavy portion. Two-phase fluid is a fluid which comprises at least two components of different densities, such that separation occurs in the swirling flow. The two different phases may be liquid-liquid, liquid-gas, liquid-solid or gas-solid. The heavy portion of the fluid may comprise the hydrocarbon liquid, while the light flow may be gas. Or, the heavy portion may be water, and the light portion hydrocarbon liquid.

There is several other embodiment of the present invention, but each embodiment operates at the same principles.

A.2.4 Kouba patent by Chevron

Chevron has taken patent on the Kouba technology. The invention is a mechanical flow conditioning technology for improving downstream separation of oil, water and gas, and swirling the bulk flow to enhance coalescence of the dispersed phase [32]. Most conventional separation systems and pipelines tend to shear and disperse coalesced droplets and stratified layers of fluid components when the fluid is passed through the flow control apparatus. Conventional flow control apparatus are typically designed such that there is a rapid change in both the flow rate and direction of a fluid mixture passing through the flow control, and energy is dissipated into the fluid. As the rate of energy dissipation increases, break-up of coalesced droplets occur and smaller droplets are created. The concept behind this patent includes reduction of forces that are responsible for droplet break-up as well as enhancing coalescence of the dispersed phase.

The design of the flow conditioning choke is such that pressure drop is produced through a combination of series and parallel swirl producing components. The impact velocity is kept small by orienting pressure dissipating orifices, and pressure losses is achieved through a series of such orifices or other restrictions, rather than taking one large loss through a single opening. Gradually pressure drop through orifices reduces the rate of energy dissipation per

unit volume, which maintains droplets in a coalesced state, and minimizes droplet break-up. The orifices also keep the impact velocity low, and droplet size is inversely proportional to the square of impact velocity. Coalescence is also enhanced due to strong fluid rotation which reduces the relative velocity differential between droplets of stratified layers of incoming fluid, and generates a centrifugal field.

The technology comprises of a flow conditioning and separation system for separating liquid components of different densities. The flow conditioning system has an inlet, an outlet and a swirl chamber extended along a curvilinear axis. The inlet and outlet cooperate with the swirl chamber and induces a swirl of the fluid mixture about the swirl axis. The flow is directed to flow circumferentially within the swirl chamber. This creates a helical swirling motion about the swirl axis. Centrifugal forces imparts on liquid components of different densities, which enhances coalescence and minimize droplet break-up. The separation apparatus separates liquids of different densities.

The flow control system may serve as a choke to reduce pressure, a flow control valve to control the rate of flow through the flow control apparatus or as an elbow to redirect the direction of the flow. The inlet and outlet may also have a plurality of orifices in series or in parallel. A schematic drawing of the present separation system with flow conditioning devices is shown in figure A-8 below.
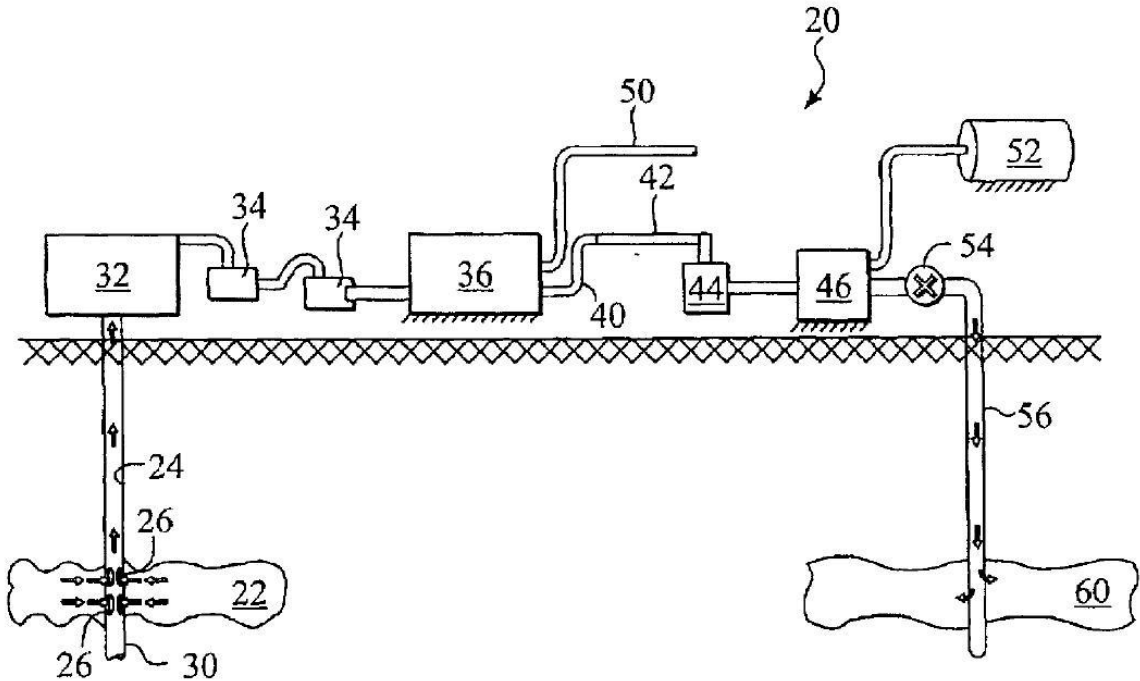
Figure A-8: A schematic drawing of the present invention

Figure A-8 above separates gases and liquids oil and water from production fluids produced in an underground formation (22) through a wellbore (24). A casing (20) with perforations (26) allow the production fluid to pass into the wellbore and out through a wellhead (32). The separation system (20) separates water, oil and gases. The separation system comprises a pair of coalescing chokes (34), a gas separator (36), a coalescing elbow (40), a coalescing conduit

(42), a coalescing control valve (44) and a water/oil separator (46). The coalescing chokes are used to reduce or step down pressure in the production fluid which leaves the wellhead at high pressure. The gas separator receives the production fluid from the valves. In this embodiment, the gas separator is a conventional horizontal separator. A pipeline (50) removes the gas, and transports it to other processing facilities. The production fluid which contains some dissolved gas is sent to a coalescing elbow which redirects the liquid in a desired direction. The fluid mixture is also her subjected to centrifugal forces which enhance droplet coalescence. The liquid production fluid is then sent through a coalescing conduit which induces swirling motions to create centrifugal forces, and separates liquids with different densities. A coalescing control valve then receives the liquid flow, and controls the rate of fluid flow, in addition to impart centrifugal forces to the liquid flow. A liquid separator, like a three-phase separator separates water and oil. The separated oil is transported to a storage tank (52). The separated water is passed through a control valve (54) which controls the disposal of water into a disposal wellbore (56). The disposal well delivers the water to a disposal formation (60).

The coalescing devices in the present invention operates on the principles of reducing the forces that are responsible for droplet break-up, and swirls the bulk flow to enhance coalescence of the dispersed phase of the production fluid. Centrifugal forces created in the swirling flow segregates the fluid components according to density, and cause the droplets to crowd together and enhance coalescence of multiple droplets into larger droplets. The performance of a downstream separator will be significantly improved.

The object of the invention is to have a system which increases the efficiency of separation of liquid phases as well as enhancing coalescence and reduce droplet break-up, as well as it is compact in size and low in weight.

A.3   Background for the polymer injection valve, developed by Total

The following sub chapters give a full review on the technologies which are background for the development of Total's polymer injection valve, as well as similar technologies and concept as the Total valve.

A.3.1   Flow control apparatus and method

A flow control valve which purpose is to control the flow of dilute polymer solutions without causing any significant degradation of the polymer has been invented by Luetzelschwab [44]. The invention comprises both an apparatus and a method which enables transport of dilute polymers with substantially no degradation. The apparatus consist of a needle valve positioned in a conduit for transport in one embodiment, and a self-adjusting flow regulator in another embodiment. The self-adjusting flow regulator contains a tapered throttle on a reciprocatable piston. The result is the need of smaller volume of polymer solution in addition to enhanced oil recovery. The present invention is illustrated in figure A-9 below.
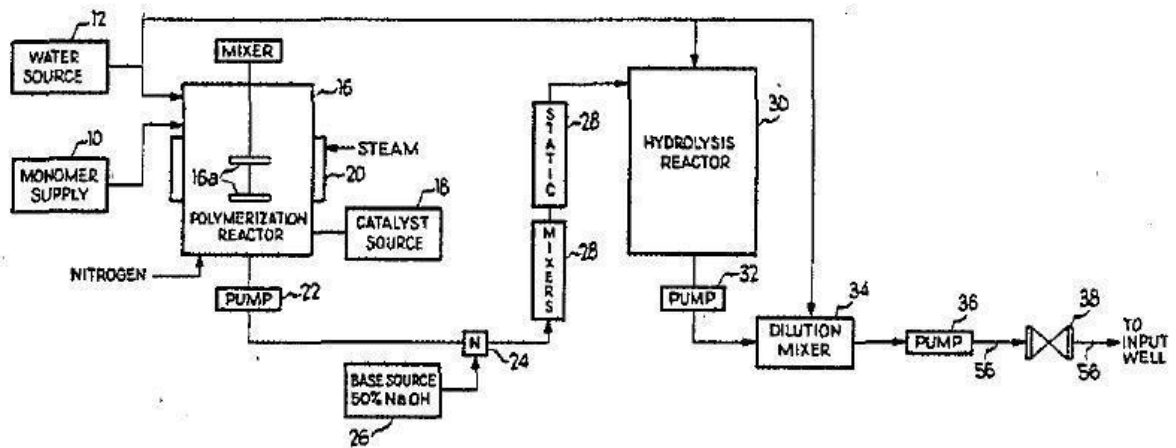
Figure A-9: The present invention by Luetzelschwab

As illustrated, figure A-9 comprises a monomer source (10), and a source of water (12). The sources are in connection with a polymerization vessel (16), which contains a stirrer (16a) and a steam jacket (20) for heating the solution mixture. A pump (22) has its inlet connected to the vessel, and its outlet connected to a mixing nozzle (24). The nozzle removes the formed polymer from the vessel and into contact with an aqueous base source (26). A static mixer (28) is in contact with the mixing nozzle and a hydrolysis reactor (30). The hydrolysis reactor dilutes the polymer. The dilute polymer is removed by a pump (32), and into a final dilution mixer (34). The final diluted polymer is then moved by a displacement pump (36) through a flow control valve, in this case a needle valve (38). From the needle valve, illustrated in figure A-10 below, the solution is injected into an input well.

Normally, the solution contains from 500 to 2000 ppm polymer, and with a rate of 10 to 30 gallons per minute. With the use of the system in figure A-9, the polymer has undergone almost no degradation when it reaches the well site. Even at pressure drops across the flow control of 100 – 150 psig (6.7-10.3 bar), there was no significant degradation of the polymer.
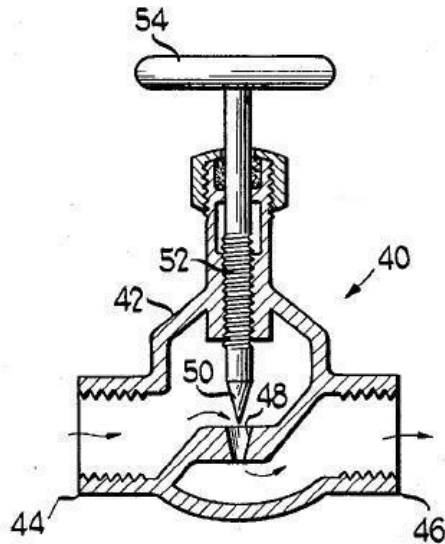
Figure A-10: The needle valve in the present invention
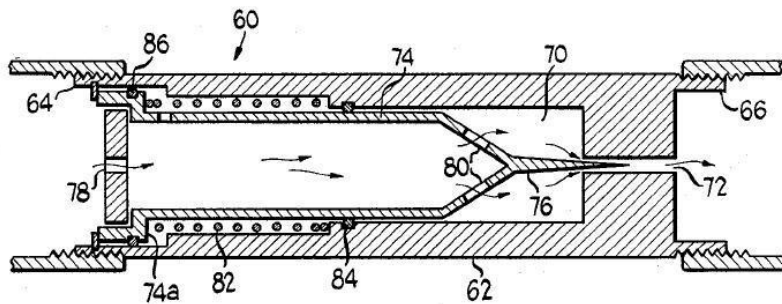
Figure A-11: The self control flow regulator in the present invention

The needle valve and the self control flow regulator are the essential parts of the present invention, and are illustrated in figures A-10 and A-11 above. The self control flow regulator has a reciprocatable piston and a tapered throttle which function is to maintain a constant pressure drop across the regulator, for transport of dilute polymer solutions with no degradation.

Tests and verification of the needle valve showed that even at pressure drop of 286 psig (20 bar), the viscosity of the polymer solution remained unchanged after passing through the valve. However, with the same pressure drop, but with the use of a blunt disc valve, the polymer solution had a decrease in viscosity of 20% when it was passed through the valve. This indicated that the needle valve contributes to no degradation, even at substantial pressure drops. Similar tests were done with globe valves, and blunt disc valves with various orifice sizes, and the results were the same.

The constant pressure drop the self control flow regulator maintains is due to a fully opened or closed position of the throttle. With an increase in fluid pressure at the passageway, a spring will urge the piston and the throttle downstream of the outlet end of the housing, and

restrict the flow of fluid through the passageway. By this, the pressure drop is constantly being maintained.

The present invention by Luetzelschwab now described, provides an efficient, both economical and practical method for controlling the flow of a polymer solution without concomitant degradation of the polymer.

However, at higher more realistic flow rates, such as 100 m³/h, the degradation of the polymer becomes significant [43]. In the verification and testing of the present invention, the flow rates were only 8 gallons per minute, which corresponds to 1.8 m³/h. The system is also susceptible to mechanical wear.

A.3.2 *Adjustable pressure reducing valve*

The pressure on a flowing liquid, such as a polymer solution, can be reduced by the use of a packing of displaceable solid shapes such as sand or beads, in the conduit, such that the pressure drop, hence the degradation of the polymer is decreased. Seawood Seawell has patented a valve which compromises packing of displaceable solid shapes within at least a plurality of conduits interconnected in a parallel flow pattern [45]. Shut-off valves at the inlets of the conduits may displace the solid shapes into conduits called storage legs. By adjusting the length of the packing of the solid shapes, the pressure drop can be controlled. This subjects the solution to minimal shear force, thus minimal degradation. The present invention to Seawood Seawell is illustrated in figure A-12 below.
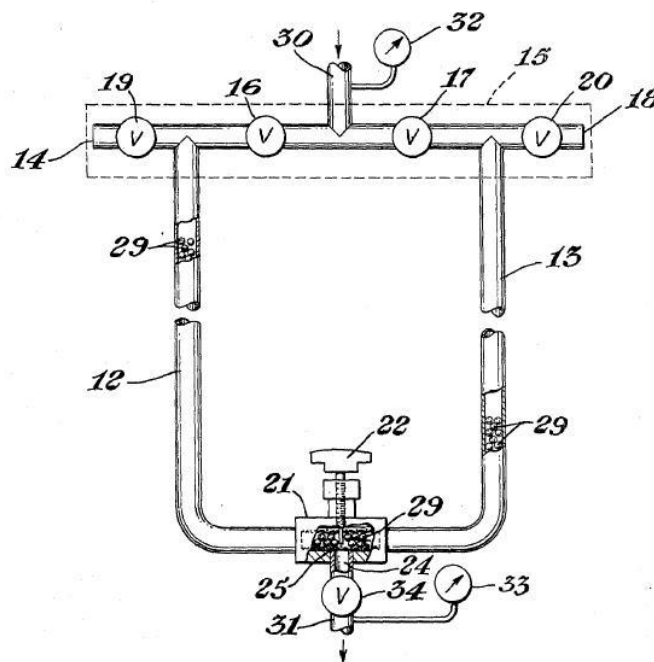
Figure A-12: Adjustable pressure reducing valve (Seawell)

Excessive shearing in conventional devices may cause significant degradation of high molecular weight polymers. The present invention is a valve which is especially adapted for reducing the pressure of polymer solutions, with minimal shear and degradation.

In water flooding, depressurizing devices are used on pressurized water. Conventional depressurizing devices such as orifices, nozzles and valves may give high shearing of the liquid, when the pressure in decreased across the devices. In the case with polymers, they will loose their desirable properties, hence a reduction in viscosity will occur. It is well known that passing the polymer solution through a porous bed will minimize the degradation of polymer during pressure reduction. The pressure reducing gradient will then be increased which will result in less shear forces than in conventional devices.

The present invention compromises a plurality of liquid conduits which are connected in parallel for fluid flow, and where at least one of the conduits contains a packing of pressure displaceable solid shapes. A valve at the inlet diverge the fluid into the conduits, and at the outlet there is an outlet manifold where the parallel conduits communicates, and which is capable of passing the solid shapes. In addition there is a liquid permeable retainer which retains the solid shapes, while letting the fluid pass through. The solid shapes are blocked and unblocked by gates and the end of the conduits.

Referring to figure A-12 above, two conduit legs are connected in parallel for liquid flow, where one leg (12) is for fluid flow, and the other leg (13) is a storage leg. Both legs contain a partial packing of displaceable solid shapes (29). The solid shapes that are within the flow leg provides resistance to the liquid flow, while the solid shapes within the storage leg are available for adjustment of the length of the pack in the fluid leg. A valve (15) connects the two legs together; in addition the valve diverts the incoming fluid either to the fluid or storage leg, depending on the desired pressure drop. The fluid can be discharged through the bleeder vent (14 and 18) depending on which leg receives the fluid. A discharge manifold (21) provides the communication between the two legs. The manifold contains a retaining screen (25) which retains the displaceable solid shapes within the legs. An adjustable gate (22) blocks or unblocks the displacement of the displaceable solid shapes from one to another of the legs by the means of rotation. There are pressure gauges (32 and 33) at the inlet line (30) and at the outlet line (31) which function is to measure the pressure drop across the valve.

The pressure drop across the valve is adjusted by displacement of the displaceable solid shapes into the storage leg (decreasing pressure) or into the flow leg (increasing pressure drop) until the desired pressure drop is achieved.

However, even though the pressure drop can be regulated by adjusting the length of the displaceable solid, these systems are well known for degradation of polymer solutions. In addition, the system is susceptible to mechanical wear of the valve, as well as damaging of the porous medium [43].

A.3.3 *Polymer flow control apparatus*
To control the flow of dilute polymer solutions, positive-displacement flow devices has been much used, such as hydraulic pumps and motors which withdraw energy from the stream. The

energy can further be used to control the rate of flow of the stream, thus prevent or minimize degradation of the polymer in the solution. An air compressor can be incorporated to regulate the amount of energy which is withdrawn from the stream. The invention now described is especially useful for transport of partly hydrolyzed polyacrylamide in a subterranean oil bearing formation for secondary and tertiary oil recovery, and especially when the polymer solution is prepared and diluted at the oil recovery site.

Luetzelschwab has a patent on the present invention described in this chapter [46]. The invention is an apparatus which controls the flow of aqueous partially hydrolyzed polymer solution to minimize degradation of the polymer (figure A-13).The present invention utilizes a positive displacement device positioned along the flow path. The device can be flow meters, pumps, like piston pumps or vane pumps, and hydraulic motors such as piston motors or gear motors. By varying the rate at which energy is removed from the polymer stream, flow rate is obtained. The forms that remove energy may differ, but in one form the rotational work imparted on the fluid may be translated. One example of such a system is the use of a hydraulic pump which motor is coupled to an air compressor. By varying the discharge pressure of the compressor by a valve, the extraction of energy from the polymer stream can be controlled, thus the rate of flow across the motor.

Figure A-13: Hydraulic motor and air compressor used in the present invention

The energy withdrawn from the polymer stream can be utilized as a source of power. The output from the compressor can be used to power the valve which regulates the flow of polymer stream, or converted to heat, and use as a heating source.

Referring to figure A-13 above, the embodiment (10) of the flow control device is illustrated. The diluted polymer flows through the polymer inlet (11) to a positive displacement device such as a hydraulic pump or motor (12) and then to a polymer outlet (13). The solution goes from the outlet to a well head (14) for injection into an oil-bearing reservoir. Air flows into the air inlet (19) and is discharged through outlet (20). By varying the pressure to which air enters the inlet may regulate the rate at which energy is transmitted from the polymer stream. A regulator (21) such as a control valve can be positioned in the outlet to regulate the output pressure.

An air compressor (figure A-14) is used to extract energy from the motor (12), by this means, control the pressure drop, hence the flow rate.
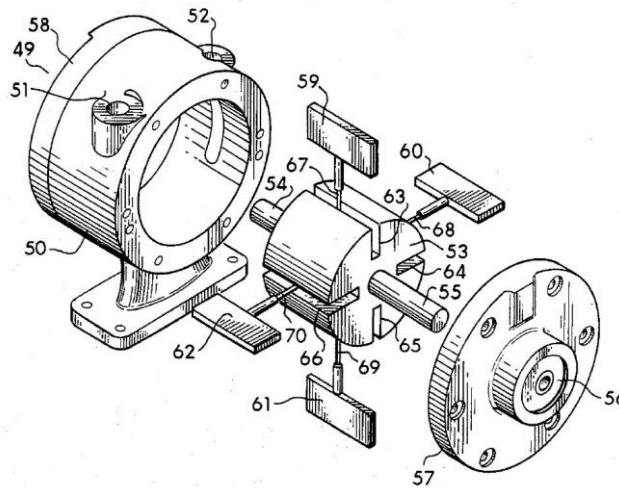
Figure A-14: An air compressor used to withdraw energy from the polymer stream

Flow control is normally regulated by control valves in conditional polymer systems, but closing of the valves contributes to increased physical resistance, and is not suitable for polymer solutions, because of excessive degradation of the polymer.

The results after verification and testing of the present invention are shown in table A-1 below.

Pressure drop across motor (psi)	Flow rate (gpm)	Changes in viscosity	
		Upstream (cp)	Downstream (cp)
66	4.3	65.1	65.7
72	5.0	60.3	59.1
88	6.0	59.3	59.3
91	5.9	64.7	64.3
110	2.8	65.1	63.3
150	3.6	60.2	59.7

Table A-1: Results after testing of the flow control apparatus, including changes in viscosity

From table A-1, it is understood that the polymer did not undergo much degradation, there is only a slight different in viscosity upstream and downstream the apparatus, even at high pressure drop, up to 150 psi (10 bar).

Even though the system recently described prevent degradation of the polymer at high pressure drops, the system does not prevent degradation of the polymer at high flow rates (> 13 m^3/h) [43].

A.3.4   Adjustable flow rate controller for polymer solutions
Conventional valves may give 50% degradation of polymer when the solution is injected into the well heads, which dramatically reduces the viscosity. It is necessary to have some control

of the rate of flow of polymer solution into the well heads, as well as to be able to quickly change the rate at which the polymer solution is injected into the wellhead. Conventional methods often use globe type valves to control the rate of flow. For hydrolyzed polyacrylamide, the sudden pressure drop across the orifice provided by the globe valve causes the polymer to break up, which leads to drastic loss in viscosity. H. L Bildartz and G. S Carlson [12] have shown that conventional injection wellheads give reductions of 26 – 41% in viscosity, and 13 – 54% reduction in screen factors. Screen factors are measurement (SF measurement) of the elongational viscosity of the polymer solution. With the use of global valves to inject and control the flow of polymer into the wellhead additional polymer has to be injected to compensate for the polymer degradation, which is economical and environmental undesirable.

Another conventional method for controlling the flow of polymer into the wellhead with minimum degradation is the use of "choke coils". Jackson has invented a coil which will give maximum 25% degradation of the polymer solution when it is injected into the well heads, in addition to controlling the flow of polymer solutions [33]. These coils give less degradation of the polymer, however, the shortcoming of the coils are that there is no adjustment to simply and quickly alter the pressure drop provided by the device. If it is necessary to change the amount of restriction of flow, the operator has to disconnect the coil from the injection line, and shorten or lengthen the coils in the device.

The invention done by Jackson (figure A-15) is a device which can vary the flow rate of shear degradable polymer solutions which will not cause an undesirable degradation of the polymer solution.
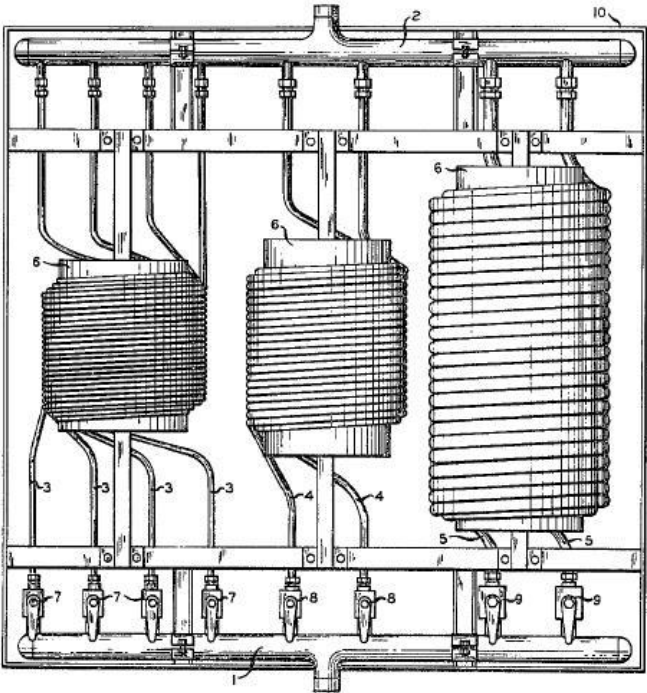
Figure A-15: Coil for polymer solutions

The device comprises of:

1) An inlet manifold (1)
2) An outlet manifold (2)
3) A plurality of tubes which provides communication between the inlet and outlet manifold (3 ,4, 5)
4) Supporting mandrels (6)
5) A valve associated with each tube (7, 8, 9)

The internal diameter of the tubes are smaller than the internal diameter of the inlet and outlet manifolds, but large enough to ensure that the viscosity of the polymer passing the tubes does not get reduced by more than 25%.

The valve is capable of opening and closing communication between the inlet and outlet manifolds. When open, the internal diameter of the valve is at least as great as the internal diameter of the associated tubes.

The inlet manifold is connected to a polymer solution source and the outlet manifold contains an outlet which provides communication between the flow control device and the wellhead.

Tests with the device have shown that both the screen factor and percent loss in viscosity was less than with conventional methods. The test confirmed that the inventive flow rate controller can be used to vary the flow of shear degradable polymer with minimal loss of viscosity. However, the system recently described is bulky and difficult to implement, as well as inflexible, such that it is difficult to fine adjust the pressure drop and flow rate [43].

A.4   Background for Typhonix 's flow control device (Shark)

The following sub chapters gives a fully review of the technologies behind the fluid flow control device (Shark), as well as similar technologies and concept as Typhonix's flow control device.

A.4.1   Spiral mixer for floc conditioning

This invention by Lean et al., is a system and method for treatment of water containing particles [49]. The device contains an inlet which receives the source water, a spiral mixer, buffer tank, spiral separator and an outlet having two paths, one path for the effluent, and one path for the waste water containing the aggregated floc particles. The spiral mixer mixes the source water with a coagulant material and an alkalinity material, and performs in-line coagulation and flocculation processes within the spiral channels. The buffer tank receives the aggregates from the mixer, and allows them to grow beyond the cut-off size of the spiral separator. The separator separates the content from the buffer tank into affluent and waste water with aggregated floc particles. The invention is illustrated in figure A-16 below.
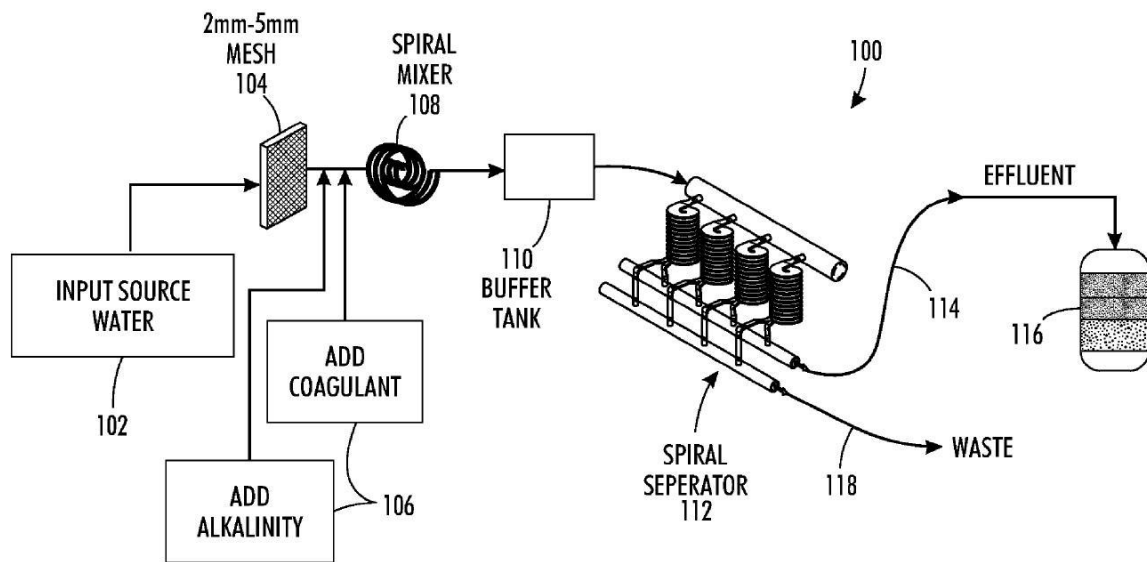
Figure A-16: The spiral mixer patented by Lean et al., for treatment of water containing particles

Traditional water treatment plants include processes like coagulation, flocculation, sedimentation and physical filtration. All of these processes need physical structures like coagulation basins and sedimentation basins. Flocculation occurs when flocculants are added to the flocculation basins. Often, long chains of polymer are used as flocculants, the polymer chains will anchor the flocs to form larger aggregates, which will sediment faster in the sedimentation basin. The three stages, coagulation, flocculation and sedimentation have a hydraulic retention time of 5-10 hours, depending on the input water quality and the facility. This requires high physical footprint as well as a high initial infrastructure costs.

This invention benefit over the traditional water treatment plants in high scalability, modularity, small footprint, high throughput, purely fluidic, continuous flow, membrane-less, size selective cut-off and accelerated agglomeration kinetics. The system will work with particulates of any density, but especially those with neutral buoyancy. The result of all of these features is reduced coagulant dosage, up to 50% reduction in coagulant dosage to achieve the same turbidity reduction as with traditional treatment plants. Extraction of micron sized pin flocs in fluidic structures eliminates the need for flocculation and sedimentation steps. The result is significant savings in land and chemical costs, operational overhead as well as faster processing time from raw to treated water.

The aggregation of flocs is orthokinetic (shear driven) in this invention. In orthokinetic aggregation, the floc formation is very fast compared to perikinetic aggregation (diffusion driven), which is the conventional floc formation mechanism. By forcing the water and the coagulant through channels, chaotic flows are generated, which facilitates turbulent dispersion of chemicals in the flow. This reduces the contact time and the hydraulic retention time, a few seconds is sufficient to achieve effective mixing.

The invention is with the spiral mixer and spiral separator is illustrated in figure A-16 above. The inlet source water is received at the inlet (102) and goes through a mesh filter (104) where larger particles are filtered from the water. The dosing system (106) is adding a base continuously in-line to regulate the pH of the source water throughout the process, as well as a coagulant before the spiral mixer and after the addition of the base. The alkaline source water with added coagulant is then received by the spiral mixer which serves a dual purpose. The first purpose of the mixer is to provide flash mixing. The incoming source water is angled at the inlet to cause chaotic mixing when the water impinges on a lower spiral channel wall of spiral mixer. The second purpose is to achieve a high shear driven fluidic flow in the channels. The channels are custom designed to achieve a shear rate which enhances the growth of floc particles with a narrow and uniform size range. To achieve a high efficiency separation in the spiral separator, the floc sizes should exceed the cut-off size for the downstream spiral. An outlet from the spiral mixer is connected to an optional buffer tank (110), which receives the aggregated floc particles such that they can grow beyond the cut-off size. From the buffer tank, an outlet is connected to the spiral separator (112) which has an effluent output (114) and a waste water output (118). The effluent output directs the separated effluent from the spiral separator to a filtering mechanism (116).

The structure of the embodiment may be stacked or parallel, achieved by various fluidic structures, implementations and selected fabrications techniques. It will be possible to scale the embodiment to a microscale (0-10 mL/min), miniscale (10-1000 mL/min) and macroscale (1-10 L/min) single-channel flow rates, dependent on the treatment process.

It is contemplated that the device is a planar embodiment with convenient stacking techniques which allows for parallel operation. Planar circular arcs in the range of 180 to 360 degrees allows for sequential stages of transverse flow pattern, steady state flow velocity and several circulatory passes to sweep particles to a desired position in the fluid flow. Other embodiments used are helical spirals. Figure A-17 below illustrates a single planar spiral mixer device used in the invention.
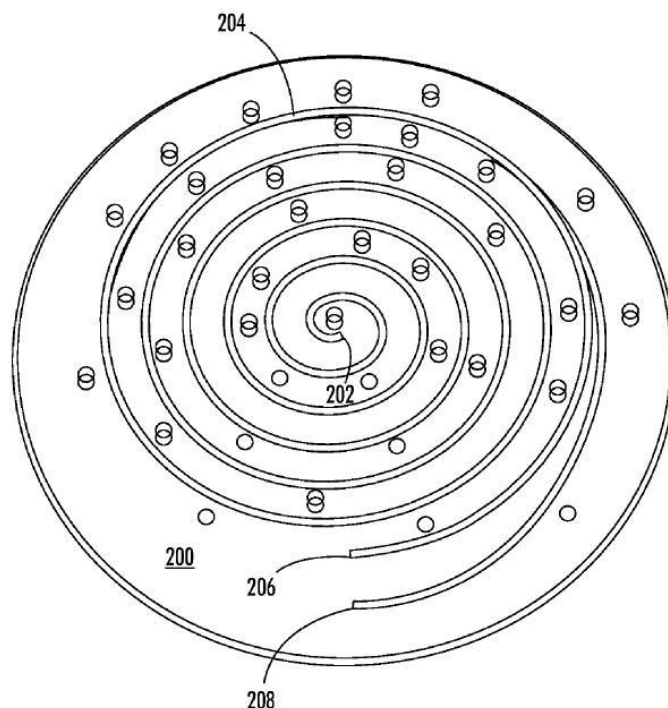
Figure A-17: Single planar spiral mixer device used in the present embodiment

The illustrated spiral mixer has an inlet (202), a curved or spiral portion (204) and an outlet (206, 208). The angle at the entrance region is 90 degrees to create sufficient turbulence, which provides chaotic mixing of coagulant and the suspended particles in the source water.

The spiral portion may take any form, and can be diverging and converging. The location for the inlet and outlets may also be interchanged for decreasing or increasing centrifugal forces, depending on the application. For a higher throughput of the fluid, the planar spiral may also be stacked (200) in a parallel manner to allow for N-layers of parallel processing.

The spiral separator is illustrated in figure A-18 and A-19 below. In the figures, the spiral separator (300) takes the form of e helical spiral. The spiral body portion (304) has an inlet (306), a first outlet (308) and a second outlet (310). This single channel helical structure resembles the shape of a coiled spring.
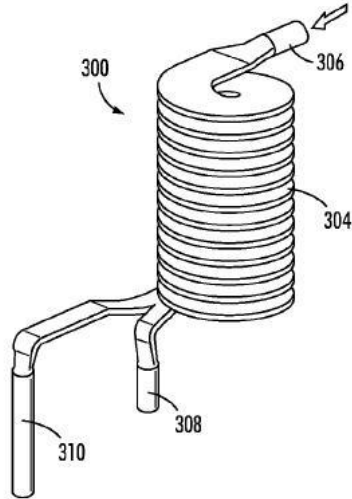
Figure A-18: The spiral separator device

Figure A-19 below illustrates the same spiral separator as figure A-18 above, the only difference is that the device shown in figure A-19 is a parallel arrangement to increase the throughput of the system.
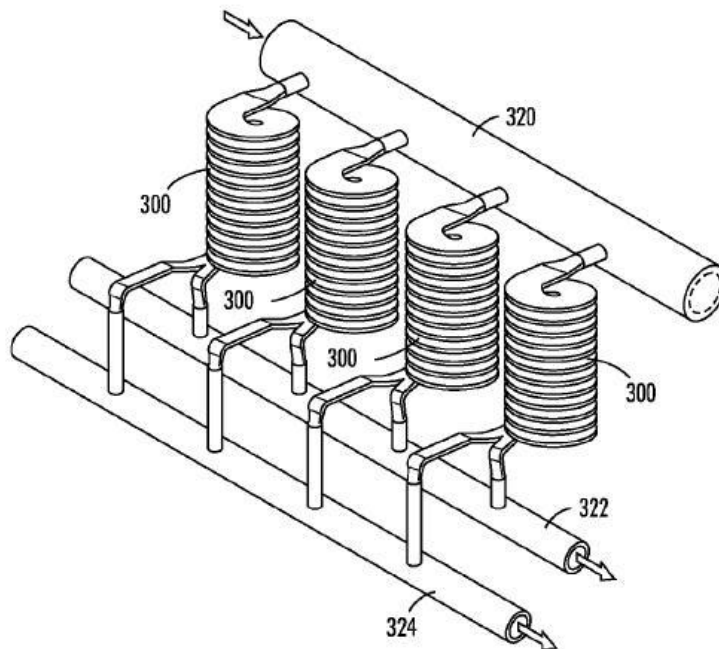
Figure A-19: A spiral separator arranged in parallel to increase the throughput of the system

The spiral devices (300) are all connected to a main input fluid manifold (320). The first outlets of the device are connected to a first main outlet (322), and the second outlets of the device are connected to a second main outlet (324).

The described embodiments use the curved channels of the spiral separator to introduce a centrifugal force upon the suspended particles in the flowing fluid, especially neutrally

buoyant particles, which are particles with the same density as water or the fluid they are suspended in. Adjustment of the geometry of the channels as well as the velocity is also techniques used to separate particles from the fluid flow. The forces utilized in these techniques are centrifugal forces and pressure driven forces, among others.

A tubular pinch effect causes the neutrally buoyant particles to flow in a tubular band offset from the center of the channel. This causes a asymmetric inertial migration of the tubular band towards the inner wall of the channel. The result is a narrow band of suspended particles, which is easily extracted. The principle behind the separation is a combination of centrifugal and fluidic forces, which causes an asymmetric inertial equilibrium near the inner wall. The angled inlet is also contributing to the band formation, due to a Coanda effect. That is, the wall friction is used to attach the impinging flow.

The embodiment described above may also have an alternative mixing-spiral separation system. The spiral mixer can consist of a plurality of stacked spiral mixer components, as illustrated in figure A-20 below.
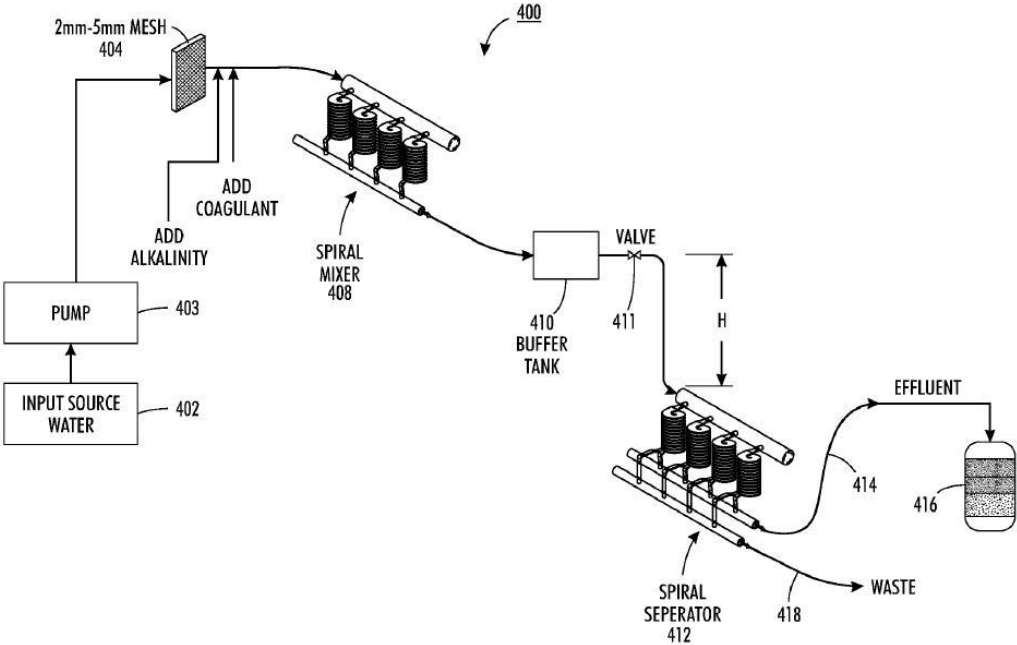
Figure A-20: The embodiment with a plurality of stacked spiral mixer components

The concept and operation is similar to the one described in figure A-16 above, but the advantage with this embodiment is that several stacked spiral-mixer components (408) results in higher mixer throughput, and an overall higher throughput of the system.

To summarize, the present embodiments result in at least the following aspects:

1. A shear rate that can be customized to form uniform-sized aggregates
2. A flow rate that can be customized
3. A high throughput by vertical stacking of channels
4. Converging (inward) or diverging (outward) spirals

5. A minimal diffusion time in the channels, which reduces the contact time. The chemicals in the water are also thoroughly mixed with the water within the retention time in the spiral mixer.

6. An in-line coagulation, flocculation and sedimentation water treatment system without flocculation and sedimentation basins, as well as reduced process time. The result is the need for reduced space, as well as reduced costs.

A.4.2 Platform technology for industrial separations

This invention by Lean et al., is a system for treatment of a fluid stream with a spiral mixer [50]. The fluid flow is received by a spiral mixer which mixes and conditions the input stream. The mixed fluid stream is then input to a spiral separator which separates the fluid stream into at least two fluid streams. One stream having removed all the particulates, while the other stream has the particulates in the stream concentrated. The present invention is illustrated in figure A-21 below.
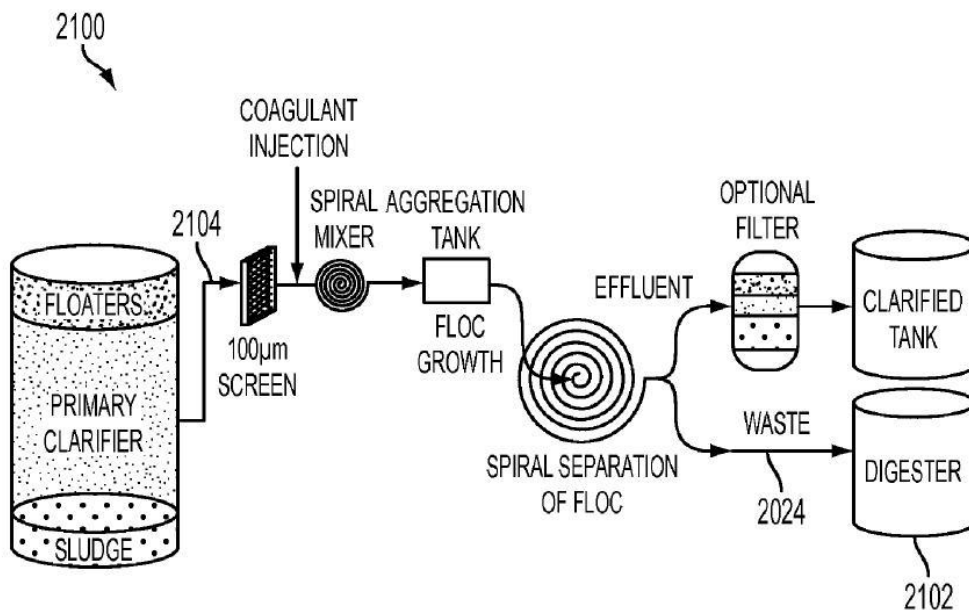
Figure A-21: The system invented by Lean et al., which includes a spiral mixer and spiral separator

The spiral mixers, illustrated in figure A-22 below, allow for turbulent mixing of input water and injected chemical. The helical spiral is designed with six turns, but other numbers of turns are also possible, as long as sufficient mixing and conditioning is accomplished for the specific implementation. The channels in this design are square channels in cross section, however, other channel cross section design may also be used.
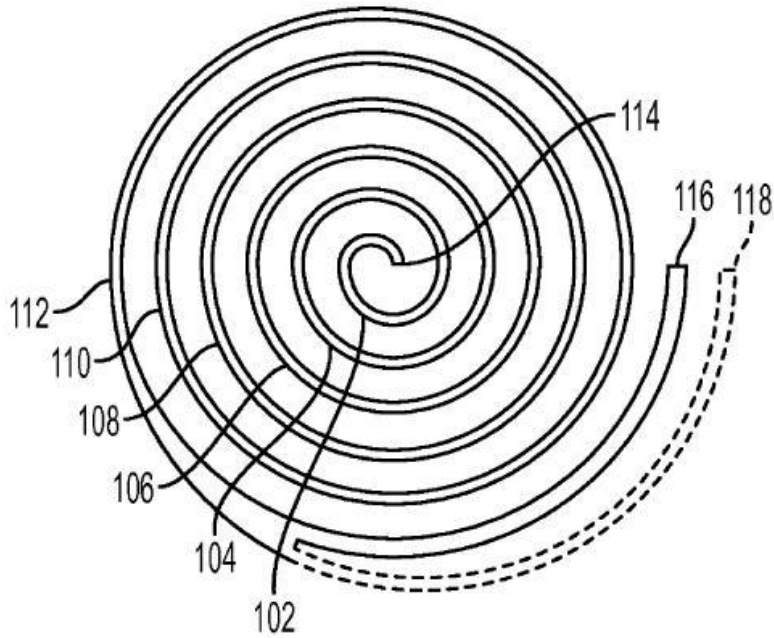
Figure A-22: Top view of the spiral mixer-conditioner in the present invention

The fluid flow enters the mixer at the inlet (114), and exits at the outlet (116). The mixing takes place in the two first turns (102, 104). Here, the fluid flow regime has a high Dean number (> 150), which means a turbulent regime. The Dean number (equation A.1) is a dimensionless quantity in fluid mechanism, and is used to study the flow in curved pipes and channels.

$$De = \frac{\rho V D}{\mu} \left(\frac{D}{2R}\right)^{1/2} \qquad (A.1)$$

Where:

De = Deans number
ρ = the density of the fluid
V = the axial velocity scale
D = the hydraulic diameter
μ = the dynamic viscosity
R = the radius of the curvature of the path of the channel

Figure A-23 below illustrates the cross sectional view of the velocity distribution of the fluid flow within the channel cross-section of the spiral-mixer conditioner.
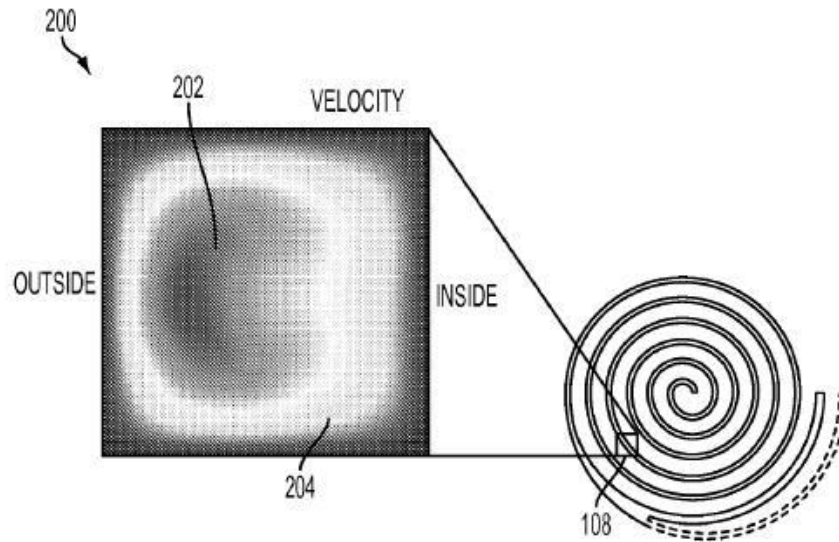
Figure A-23: Cross sectional view of the velocity distribution within the channel

The flow velocity occurs at turn 108, and on the left side of the channel. The darker image (202) represents high velocity of the flow, while the lighter image (204) represents lower or almost zero velocity. This flow pattern and velocity profile is due to centrifugal forces, which moves towards the outer side of the channel.
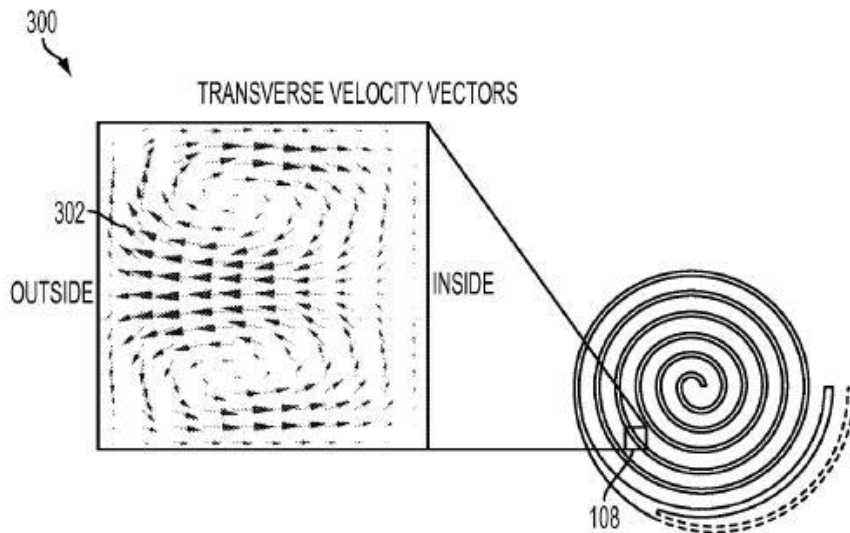
Figure A-24: Illustration of the transverse velocity vectors

The transverse velocity vectors for the same flow and cross-section as in figure A-23 is illustrated above in figure A-24. Here, the neutrally buoyant particles move along the velocity vectors, identified by the arrow movement (302).

In the two first rounds of the spiral (102, 104), the forces do not balance, and due to that, the particles are not in equilibrium and continuous to move around. From round three to six, the forces in the channel enter a state of force equilibrium, and the particles are allowed to move closer to one side wall and enter a stagnation path within the fluid flow path. This means that

the transverse velocity is very high in the two first rounds, but when the curvature radius increases, the flow enters a steady state laminar regime. Here, shear stress is employed for conditioning of the particles within the flow. The centrifugal forces decreases from turn three to six (106-112), which creates a force balance. The neutrally buoyant particles reaches equilibrium due to the decrease in centrifugal forces, and the decrease in Dean Number below the critical value of 150.

Aggregation of particles by the spiral mixer-conditioner can be achieved in two ways. By changing the geometry of the cross section of the spiral mixer or by change the flow rate speed, the shear rate, hence the aggregation of particles can be controlled. The size of the aggregate leaving the mixer can be related to the shear rate, which is the gradient of the transverse velocity. This is illustrated in figure A-25 below. As the shear rate increases, the size of the aggregates decreases. By increasing the flow rate velocity within the channels, the shear rate increases, and particles tend to break up in smaller aggregates.
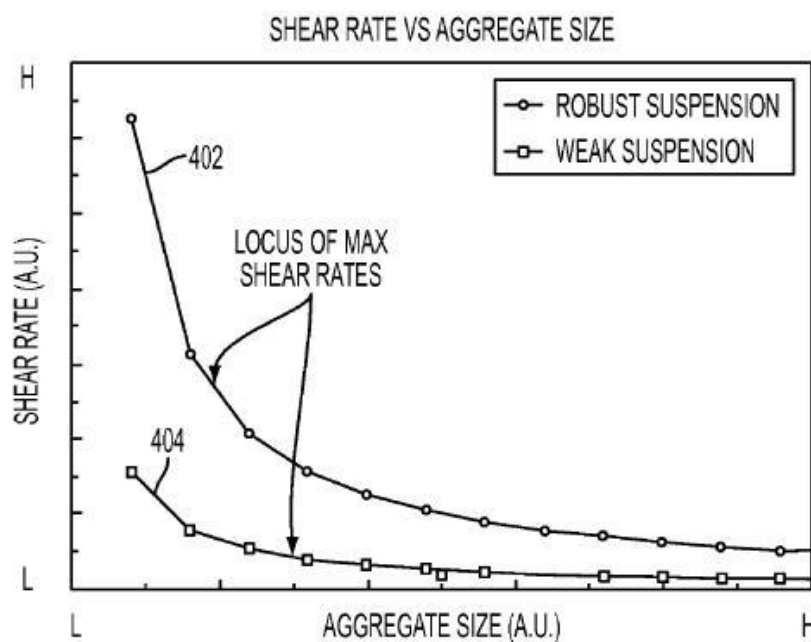
Figure A-25: Aggregate size as a function of shear rate

By controlling the flow rate, the shear rate can be designed and controlled. The result is dense uniformly-sized aggregates which are efficient separated by a downstream spiral separator.

The present invention with the spiral mixer-conditioner and spiral mixer separator offers the following characteristics:

1. Aggregation of sub-micron organic/inorganic particles upstream a spiral separator
2. Up to 50 % reduction in coagulant chemicals due to the spiral mixer compared to standard jar test protocol
3. No normal flocculation or sedimentation steps needed, less occupation of space and lower processing costs

4. Fast process – less process time, continuous flow, small footprint, low power and low pressure
5. A concentrated waste stream

Due to less occupation of space and lower costs associated with the process and operation, the present embodiment is well suited for platforms, where the operation cost is proportional with the size of the equipment.

A.5   Full review of the Bachelor thesis

Vladimir Marchenkov (bachelor thesis, 2012) has studied dispersion phenomenon in flow of oil and water through pipes and restrictions [51]. A specific characterization rig was built in the Typhonix laboratory, and different concentrations of oil-in-water emulsions using Kobbe and Grane crudes were used. The effect of different restriction sizes and lengths were studied along with several different flow rates. Laser diffraction measured the droplet-size distribution.

The experiments carried out showed that higher oil concentration yield in bigger oil droplet sizes. It also showed that oil and water mixing condition plays a crucial role on droplet sizes and distributions upstream of the restriction. It was found that droplet sizes upstream and downstream a needle valve was almost unchanged, however, a gate valve gave a clear difference in droplet size distribution downstream the valve. Further, it was found that the droplet residence time in the turbulent zone within the restriction had a major effect of the droplet size distribution downstream the restriction. In some experiments with prolonged residence time, droplet coalescence was the result, while in some cases, droplet break-up occurred.

The experiments were carried out with 1" coils with spiral-shaped pipe sections with different cross-sectional area and lengths. The use of 1" coils gave minimal pressure drop across the coil. The pipes were cut into four equal pieces and coiled. Coiling of the pipes allowed for easier handling of pipe, as well as freeing-up place in the characterization rig. It also allowed for studying the effect of different lengths of the restrictions on oil-in-water emulsions. A 10mm (OD) pipe with length of 17.55 m was chosen as a control pipe with a control volume of 882.2 ml. Based on this control volume, different lengths of other pipes were calculated, and cut and coiled in the same manner as the control pipe. The different sizes of the test pipes were 1" straight pipe, 6mm, 8 mm, 10mm, 12mm, and 15mm and 1". The use of test pipes smaller than 1" allowed for relatively low flow rates, while still maintaining flow phenomenon in pipes used for industrial applications. The coiled pipes were connected to the characterization rig via conical transition joint, denoted "tails", and 1" joint pipe. This is illustrated in figure A-26 below.
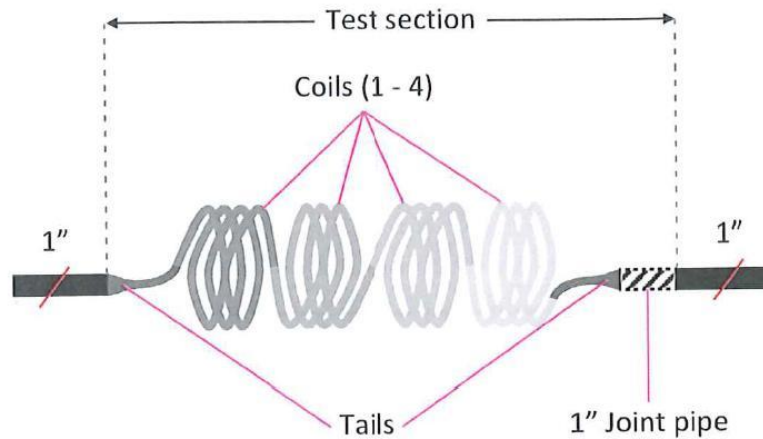
Figure A-26: Connection of coils to the characterization rig via "tails"

The flow from the 1" to smaller pipe sizes may give flow abruption, hence much shear and droplet break-up. To avoid abrupt changes and to ensure a smooth flow in the pipes, the conical transition joint was special made for each pipe size. The cone angles were approximately 5°, and together with different lengths of 1" joint pipes, the desired quantity of coils were connected. Differences in flow rate were thought to highlight flow phenomenon in the test components, due to produced turbulence with different energy dissipation rates per unit mass.

A constant flow rate together with different pipe internal diameters will also affect flow velocity in pipes, hence flow type. Calculations were carried out to see what flow the different pipe sizes were expected to give. All the different pipe sizes had Reynolds number which corresponds to turbulent flow. Especially the 6mm pipe had high Reynolds number, so high turbulence was expected when using this pipe size.

A.5.1 Test parameters
The flow parameters that were chosen for the tests, and the mixing conditions are presented in table A-2 and A-3 below.

Flow rate [l/h]		Q_1	Q_2	Q_3
		500	1000	2000
Isokinetic sampling rate [l/h]		102	205	409
		Oil injection rate [ml/min]		
O/W	200	1.67	3.33	6.67
concentration	600	5.0	10	20
[ppm]	1500	12.5	25	50

Table A-2: Flow parameters for the experimental tests

Abbreviation in table	Mixing conditions
Mixing condition 1/MixValve 1	Gate valve
Mixing condition 2/MixValve 2	Needle valve
Mix condition 3/¼"	3 – ¼" straight pipe
Mix condition 4	1" straight pipe

Table A-3: The different mixing conditions

A.5.2 Test results

The experiments with 1" straight pipe, gave as expected no registration of pressure loss (0.00 bar) by the differential transmitters.

A.5.2.1 *Test results for Q_1 (500 l/h)*

Two different concentrations of Kobbe crude were used at this flow rate. The droplet sizes are illustrated in figure A-27 below.
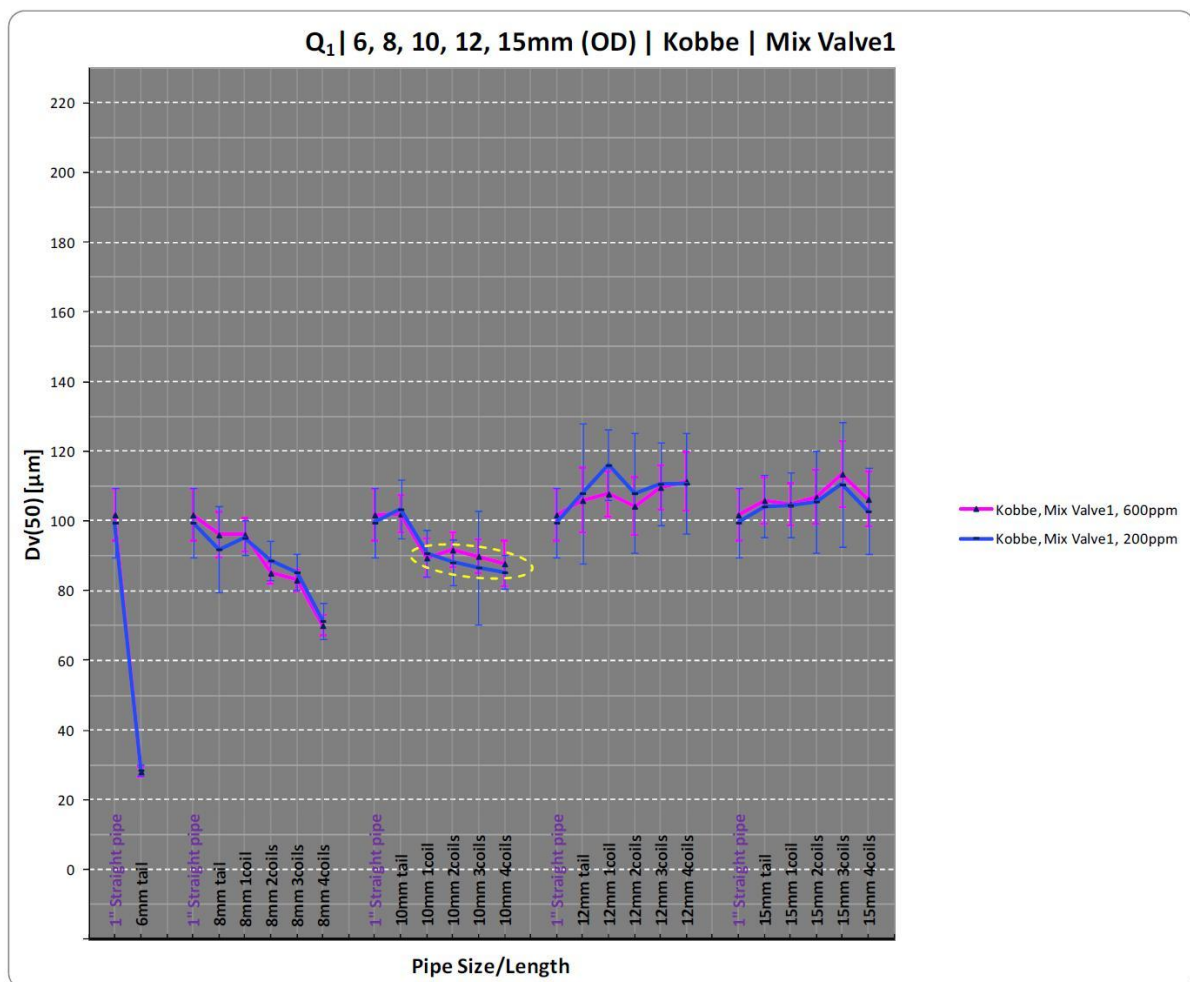
Figure A- 27: Droplet size for all pipe sizes tested at Q1

The droplet size upstream the test section was the same for all pipe sizes, 101.74 µm for 600 ppm and 99.55 µm for 200 ppm. As can be seen from the figure, droplet break-up was the trend in 6, 8 and 10 mm pipe sizes. However, in the 10 mm pipe, a plateau-like region was observed after addition of more coils. This could mean that the droplet would not break-up if consequent coils were attached. For the 12 mm and 15 mm, droplet coalescence was the trend.

When the number of coils attached increased, such as the 4th 15 mm coil, no more coalescence was observed, instead droplet break-up occurred. The reason why is difficult to explain, but it can be that the droplets created in the 3rd coil were the most stable, and that turbulence during residence in the 4th coil caused the droplets to break-up. It can also be random effects resulting from the test conditions. The tests also show that the larger the outer diameter of the pipe is, the more coalescence occurs.

A.5.2.1 Test results for Q_2 (1000 l/h)

Three different concentrations of Kobbe and Grane crude were used at this flow rate. The droplet sizes for all the tests done at Q_2 are illustrated in figure A-28 below.

Figure A- 28: Droplet size for all pipe sizes tested at Q2

Kobbe ¼" pipe, mix condition 3

From the chart above, it is illustrated that droplet break-up only occurred in the 6mm pipe for all the different concentrations. Droplet break-up occurred only at the lowest concentration (200 ppm) in the other pipe sizes. The highest concentration (1500 ppm) gave clear coalescence in every pipe sizes except for the 6 mm pipe which only had droplet break-up. Because of little change in pressure drop when consequent coils of 12, 15 and 1" pipes were added to the test section, only experiments with all four coils were conducted for these pipe

sizes. These tests revealed that coalescence is the main mechanism at this flow rate, especially at high oil concentration.

Kobbe mix valve 2, mix condition 2

As can be seen from the chart above, the main trend was droplet break-up for 6, 8 and 10 mm pipes. Both coalescence and droplet break-up were observed in the 12 mm pipe, while only coalescence was observed in 15 mm and 1" pipe, in the latter more defined coalescence was observed.

Grane ¼" pipe, mix condition 3

For all concentration, droplet break-up was the sole mechanism for the 6 mm pipe. The droplet size was of little variations at low oil concentration (200 ppm) in all pipe sizes. In all pipe sizes, beside for 6 mm, coalescence was observed at high oil concentration (1500 ppm). In the 10 mm pipe, droplet break-up was observed surprisingly, when the 4th coil was connected to the test section. This was not observed when Kobbe crude was used under the same test conditions, but is similar to the results presented in figure A-27.

Grane mix valve 2, mix condition 2

Under these test conditions, droplet break-up was the sole mechanism in 6 and 8 mm pipes, as can be seen in the chart above. For the other pipe sizes, droplet break-up was observed at the two lowest oil concentrations (200 and 600 ppm), while coalescence was observed in the same pipes at the highest oil concentration (1500 ppm). In 10 mm pipe, both droplet break-up and coalescence were observed. Again droplet break-up occurred when the 4th coil was added to the test section.

Comparing the results of Kobbe and Grane, mixing condition 2 and 3

During comparison of the results, similar trends are found in almost all the pipes. The biggest difference is found during mixing condition 2, where differentiation is observed between Kobbe and Grane oil. This differentiation is marked yellow in the chart above. Difference in oil viscosity may be the explanation of this differentiation, Kobbe is a light crude, while Grane is a heavy crude. At mixing condition 3, almost exact trends are observed between the two different oils.

A.5.2.2 *Test results for Q_3 (2000 l/h)*
Two different concentrations of Kobbe and Grane crude were used at this flow rate. The droplet sizes for all the tests done at Q_3 are illustrated in figure A-29 below.
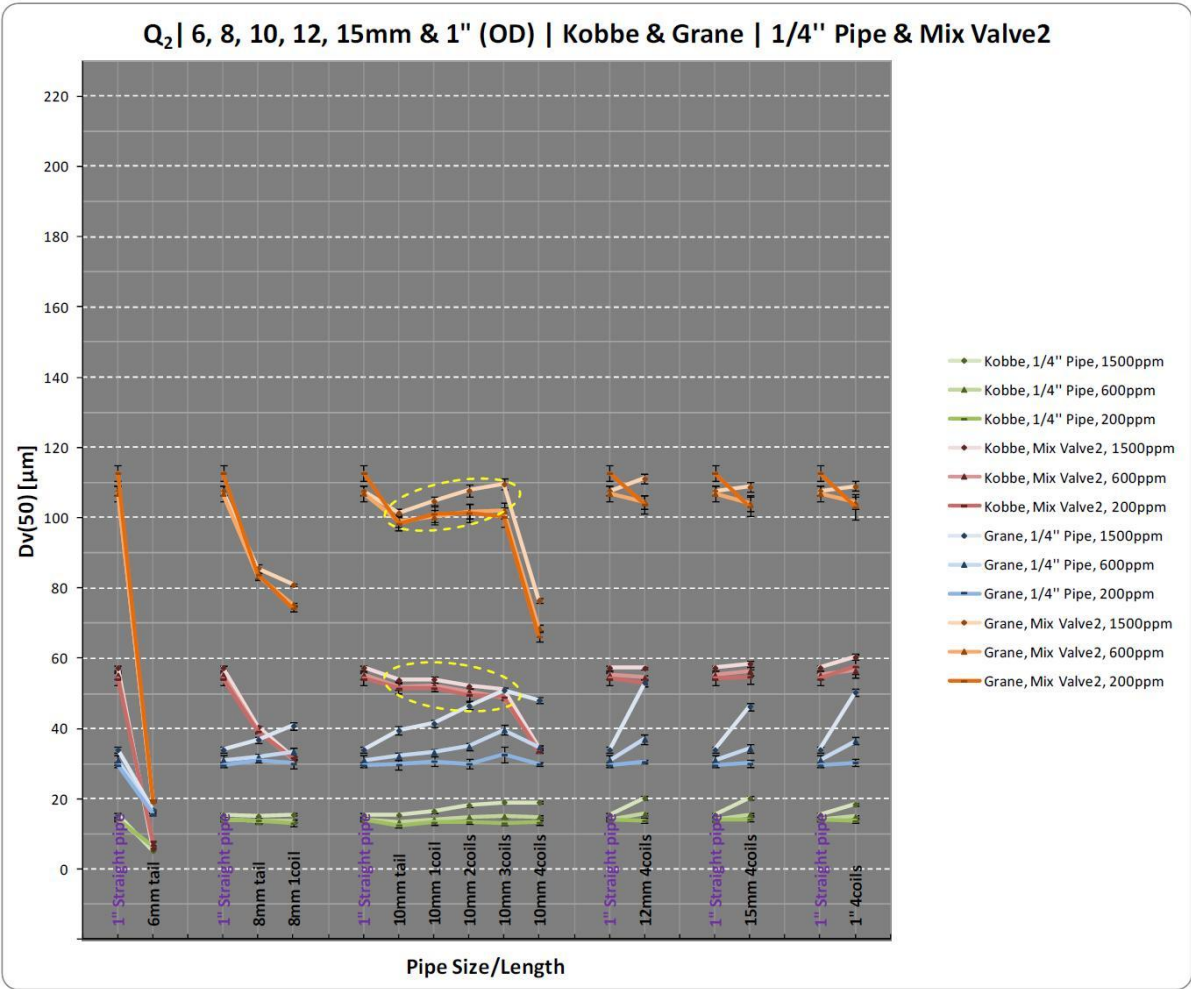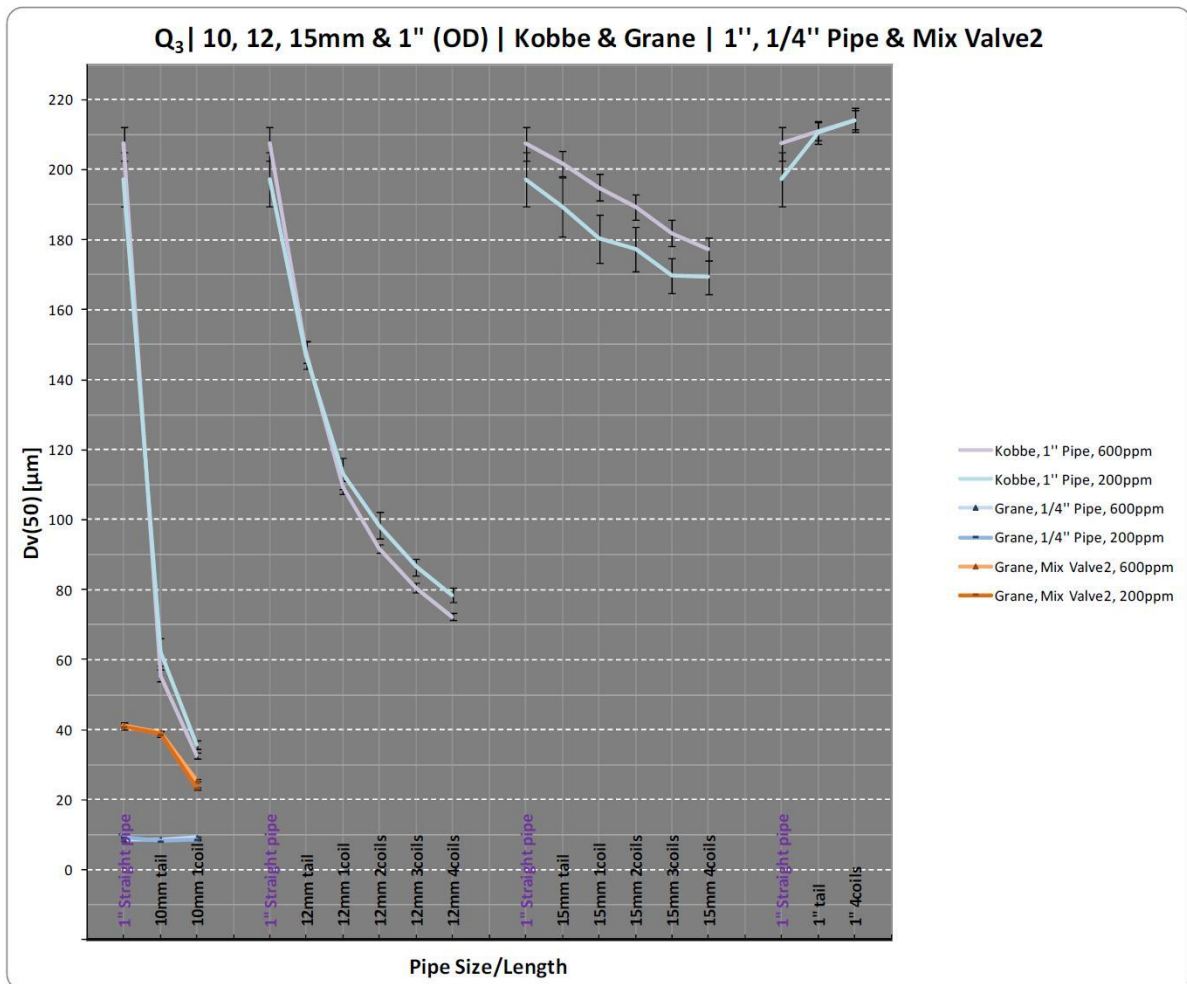
Figure A-29: Droplet size for all pipe sizes tested at Q3

Because of unstable Malvern instrument measurement with Mix Valve 1, this valve was chosen to be removed. The removal led to almost a doubling in droplet size upstream the test section. Size of the droplets upstream the test-section was equal for all pipe sizes (207.42 µm for 600 ppm, and 197.34 µm for 200 ppm). As the figure above illustrates, droplet break-up was the main mechanism observed in 10, 12 and 15 mm pipes, where most droplet break-up occurred in 10 mm pipe. Coalescence trend was found with the use of 1" pipe. The internal diameter of 1" tail and the four coils were the same, so it can be concluded that the coalescence is only a result of the spiral-shaped arrangement.

The results for Grane is presented in the same chart above, but because of scaling purposes, the results for Grane is also presented in figure A-30 below.
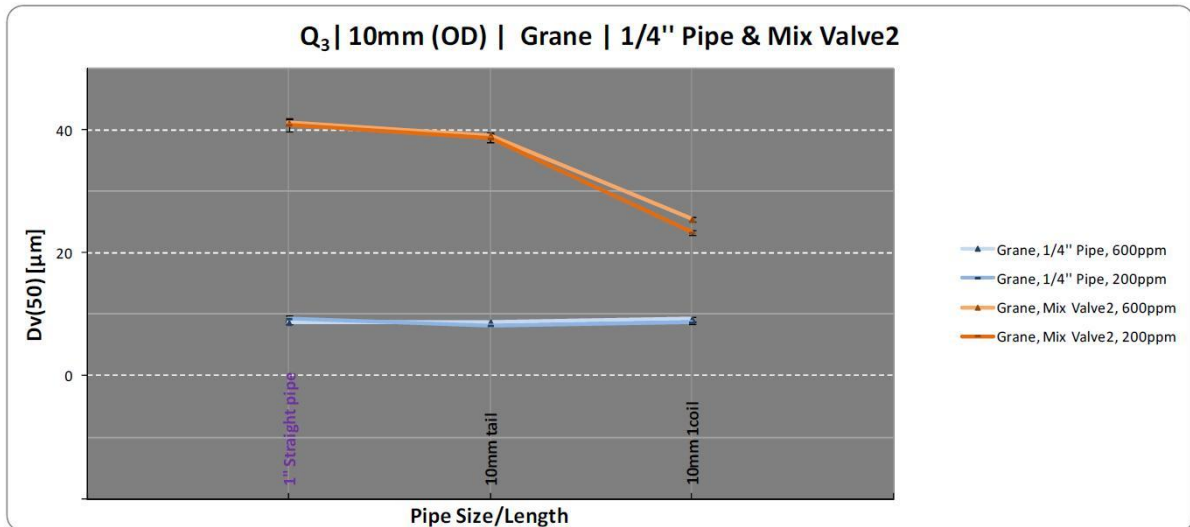
Figure A-30: Droplet size for all pipe sizes tested at Q3

The mixing condition for Grane oil upstream the test section was different than from Kobbe oil tests. This resulted in different droplet sizes upstream the test-section for Kobbe and Grane, 8.68 μm for mixing condition 3 and 41.19 μm for mixing condition 2. The difference between the two concentrations was less than 1 μm for both mixing conditions. As can be seen from the figure, almost no change was observed in 10 mm pipe when the upstream droplet size was 8.68 μm (mixing condition 3). Probably, the turbulence in the pipe at Q3 was not high enough, to break-up the already small inlet droplets. At mixing condition 2, when the upstream droplet size was 41.19 μm, droplet break-up was observed.

A.5.2.3 *Comparison of the results from all the flow rates*
All the results from all flow rates and which have been discussed in the previous sub-chapters are summarized in figure A-31 below.
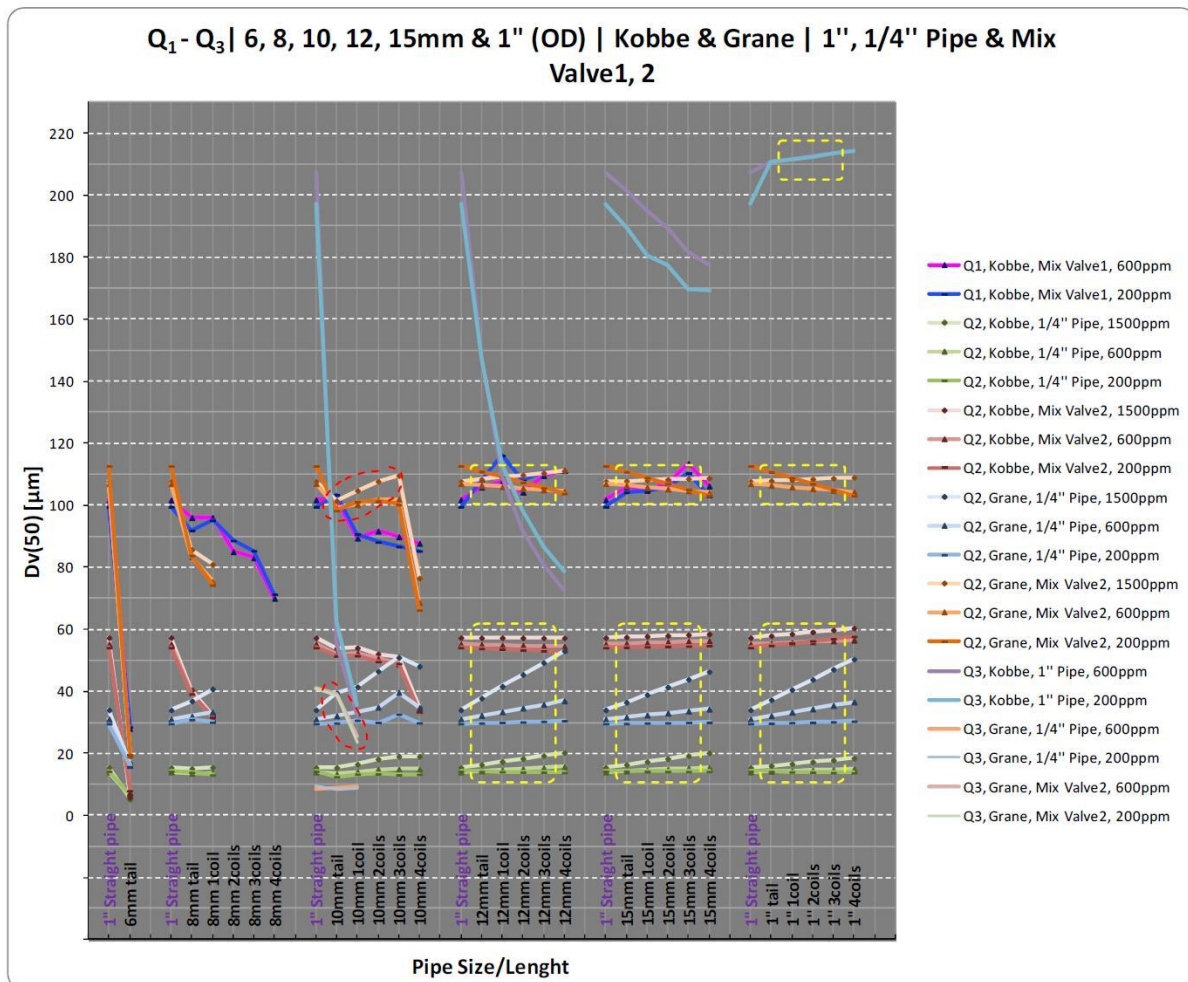
Figure A-31: Droplet size for all pipe sizes tested at Q1-Q3

To highlight the trends found during the testing, some results are extrapolates, which is marked by yellow dashes in the figure. Due to different test conditions during experimental testing stages, only the results for Grane oil at Q_2 and Q_3 (when considering Grane crude) can be directly compared, and only results for Kobbe and Grane at Q_2 (when considering flow rates) can be directly compared.

At mixing condition 2, the result with Grane at Q_2 and Q_3 varied greatly. In 10 mm tail at both flow rates, droplet break-up was the sole mechanism. However, by adding consequent coils, coalescence was observed at Q_2, while more droplet break-up was observed at Q_3 (red dashed area). Upstream the test sections, droplet sizes varied by 60-70 μm, solely because of difference in turbulence at those flow rates. As also can be seen, the concentration of 1500 ppm did result in higher droplet sizes as well as more defined trends, compared to lower concentration.

When comparing the results for 6 mm tail at Q_2 for both crudes and mixing conditions, it revealed that turbulence present in the components resulted in almost the same droplet size downstream the test-section. This is despite of variations in mixing conditions and droplet size upstream the test-section. This behavior was only seen in 6 mm pipe.

Droplet break-up through restrictions has been studied by Zande (2000). Based on his study, the conclusion was that the residence time in the turbulent zone downstream of the restriction has a minor effect of the outlet droplet size distribution. The conclusion done by Zande, was also the assumption in this thesis, together with the assumption that addition of more coils to prolong the restriction would first lead to droplet break-up, and that further prolongation of the restriction by adding more coils would eventually lead to stable droplet sizes downstream the restriction. The droplet size distribution assumption was found to be correct for mixing condition 2 (needle valve). However, it was incorrect for mixing condition 3 (1/4" pipe). This can be seen from figure A-32 below which shows the droplet size distribution in 1" pipe and 14mm pipe, with no mix and mixing condition 2 and 3 respectively, with 4 coils.
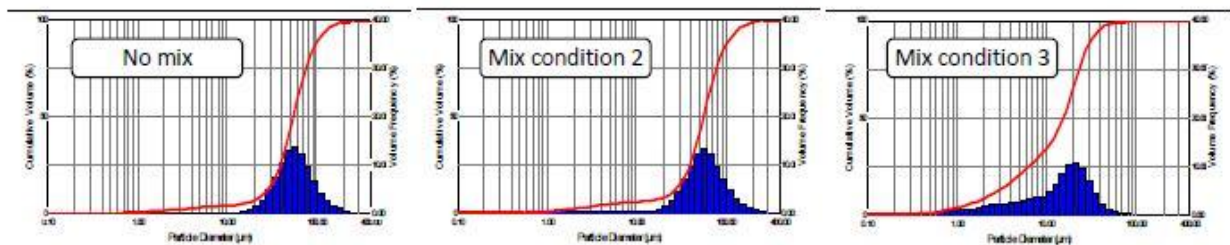
Figure A-32: Droplet size distribution for the different mix conditions

The assumption that stable droplets could be obtained by prolongation of the restriction by adding more coils was however not confirmed during the tests. Some plateau-like regions was obtained, which may suggest that equilibrium was established, and droplet size remained unchanged, not droplet break-up nor coalescence. However, the majority of the results did indicate that it is the residence time in the turbulent zone within the restriction that has a clear effect on droplet sizes. In some cases, increased residence time within the restriction resulted in coalescence, while in other cases it resulted in droplet break-up.

There are a lot of studies which confirms that most of the droplet break-up occur downstream the restriction. An abrupt expansion of the environment and a decrease in pressure, which leads to loss of energy, is the explanation for this. The effect can be minimized by the use of conical joints (tails) which connects the pipes to the test-section. Throughout this experimental work, transition joints were used to minimize droplet break-up downstream the restriction.

The turbulence level may be expressed as mean energy dissipation rate per unit mass. The different energy dissipation rate for the different flow rates and pipes used in this test is illustrated in figure A-33 below.
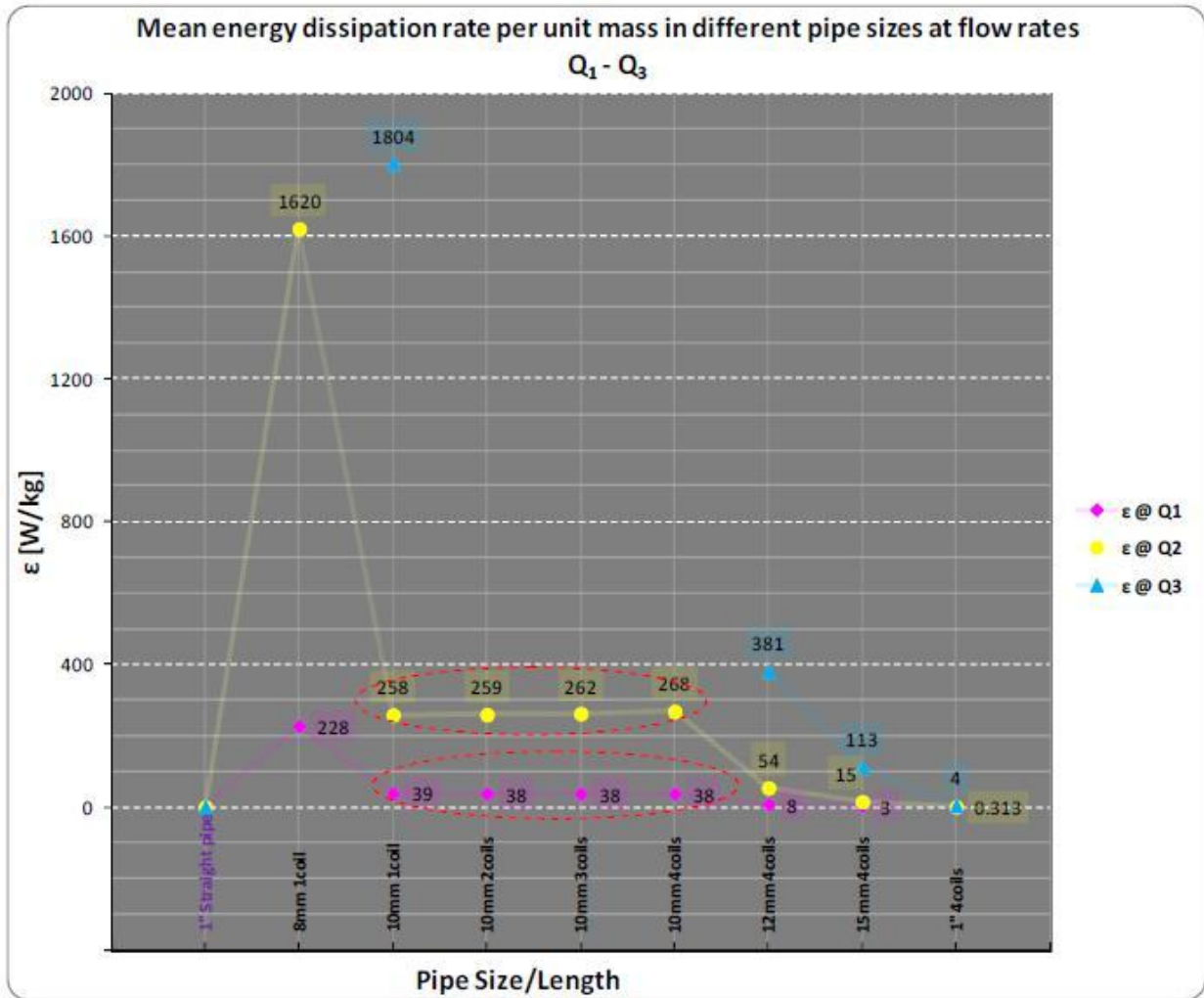
Figure A-33: Mean energy dissipation rate unit for all the pipe sizes and at all flow rates

The energy dissipation rate per unit mass for 1" straight pipe is solely based on equation calculations due to the fact that dp_{test} measurements were zero. The calculated values for Q_1, Q_2, and Q_3 were $\varepsilon_1 = 0.0842$, $\varepsilon_2 = 0.284$ and $\varepsilon_3 = 0.970$ [W/kg] respectively. However, they are not presented in the chart above.

The presented values in the chart are based on real dp_{test} measurements from the testing. The measurements were used to calculate the mean energy dissipation rate per unit mass by the use of equation A.2 below.

$$\varepsilon = \frac{dp_{test}Q}{p_cV} \qquad (A.2)$$

Where:

dp_{test} = *pressure difference over the control volume*
V = *control volume*

The control volume is 1 coil of any pipe having same control volume, and ε, and can therefore be directly compared. Theoretically, by adding consequent coils to the test-section, the result should be an increase in dp_{test} and V, by the same amount of each consequent coil added. This

means that each consequent coil added of the same pipe size should give the same ε values. Plateau-like regions in the figure (red dashes) above confirms this theory, with a little deviation. The deviations may be a result of registered dp-values because of uneven connections, coil deformations and some unregistered test-condition change.

The mean energy dissipation rate is also an important parameter to find maximum stable droplet diameter (Zande, 2000). The most stable droplet diameter can be calculated by equation A.3.

$$We_{cri^{3/5}} = \left. \frac{\sigma}{p_c} \right.^{3/5} \varepsilon^{-2/5} \qquad\qquad (A.3)$$

The experimental work carried out verified that equation X-X can not be used to calculate the maximum stable droplet diameter. The observed droplet sizes varied at different concentration levels, as well as observed coalescence in turbulent zones. Both of these effects are not incorporated in the above equation.

A.5.3 Conclusion
The main conclusion from the experimental work carried out to study dispersion phenomenon in a flow of oil and water through pipes and restrictions, are as following:

1. Oil and water mixing plays a crucial role on droplet size upstream the restriction. The higher differential pressure across the mixing section, the smaller droplets is created. High oil concentration yield droplets with larger diameter than low oil concentration. The needle valve gave almost unchanged upstream and downstream droplet size distribution, while the gate valve gave a clear difference in both droplet size distribution and uncertainty in obtained values. The uncertainty may be a result of pulse-like injection of oil into the stream. Another contribution may be low residence time in the mixing valve, as well as inappropriate mixing inside the gate valve.
2. The residence time in the turbulent zone within the restriction gave a clear effect of droplet size downstream the restriction. The assumption that droplet residence time in turbulent zones downstream the restriction had a minor effect on the outlet droplet size distribution was therefore incorrect. In some cases, prolonged residence time resulted in droplet coalescence, while in other cases, the result was droplet break-up.
3. The highest oil concentration gave the most distinguishable trends for droplet coalescence and break-up. This concentration also yielded bigger oil droplet sizes, regardless of break-up or coalescence was the mechanism.
4. The experiments with 1" coils showed that spiral-shaped test-pipes are beneficial for the coalescence effect. In all tests, where 1-4 coils were used, coalescence occurred.

A.5.4 The theory behind the bachelor thesis

A.5.4.1 Fluid flow in pipes

There are two distinctly different types of fluid flow, laminar and turbulent flow (Osborne Reynolds, 1883).

Laminar fluid flow is a smooth streamline with a highly ordered motion, in contrast to turbulent flow. Turbulent flow is characterized by a chaotic streamline, with velocity fluctuations at all points of the flow field and a disordered motion of fluid particles. Because the fluid flow is unsteady, flow properties will change with time.

Turbulent fluctuation u' is the difference between the average value of velocity along a streamline u_t over a period of time, and the mean value of velocity u at the same point. The value of turbulent fluctuation may be positive or negative, while the mean time value of u' must be zero. This leads to the following relation (equation A.4):

$$u_t = u + u' \qquad\qquad (A.4)$$

which can be evaluated for any finite time t.

Under real fluid flow will the mean velocity u vary at different points across a pipe cross-section. By summing up local, mean velocities over the entire cross-section gives average velocity U of fluid flow. Flow rate Q is the quantity of liquid flowing per unit time across any section, and can be expressed as equation A.5.

$$Q = \int_A u \, dA = AU \qquad\qquad (A.5)$$

where A = entire cross-sectional area.

By multiplying equation 8.5 with fluid density ρ, constant density flow can be expressed as the mass flow rate m (equation A.6).

$$m = \rho \int_A u dA = \rho AU = \rho Q \qquad\qquad (A.6)$$

When the density is constant, in other words incompressible, the equation of continuity can be used. The equation of continuity describes the transport of conserved quantity (mass), and can be expressed as equation A.7.

$$A_1 U_1 = A_2 U_2 = Q \qquad\qquad (A.7)$$

A.5.4.2 Reynolds number

Reynolds number is a parameter to distinguish between laminar and turbulent flow. Turbulent flow depends on pipe geometry, surface roughness, flow velocity, surface temperature and type of fluid. It has been discovered by Osborne Reynolds (1880s) that turbulent flow mainly depends on the ratio of inertial forces to viscous forces in the fluid. The ratio is expressed for

internal flow in circular pipes and is called Reynolds number, Re. Reynolds number can be expressed as equation A.8.

$$Re = \frac{F_1}{F_\mu} = \frac{UD\rho}{\mu} = \frac{UD}{v} \qquad (A.8)$$

where:
D = characteristic length of the geometry (inner diameter in case of a circular pipe)
v = Kinematic viscosity of the fluid
μ = Dynamic viscosity of the fluid

Reynolds number, Re, is a dimensionless number.

If the Reynolds number is large, inertial forces dominate, and the flow is turbulent. The viscous forces can not prevent the random and rapid fluctuation of the fluid. If the Reynolds number is small, then the flow is laminar. At laminar flows, viscous forces are large enough to suppress fluctuations.

Critical Reynolds number, Re_{cri}, is the number at which flow becomes turbulent, and varies with different geometries and flow conditions. Typically, for internal flow in a circular pipe, the critical Reynolds number is Re_{cri} = 2300 (çengel & Cimbala, 2006). However, some textbooks operates with Re_{cri} = 2000 (Finnemore, et al., 2002).

Figure A-34 below illustrates flow types at different Reynolds number intervals.
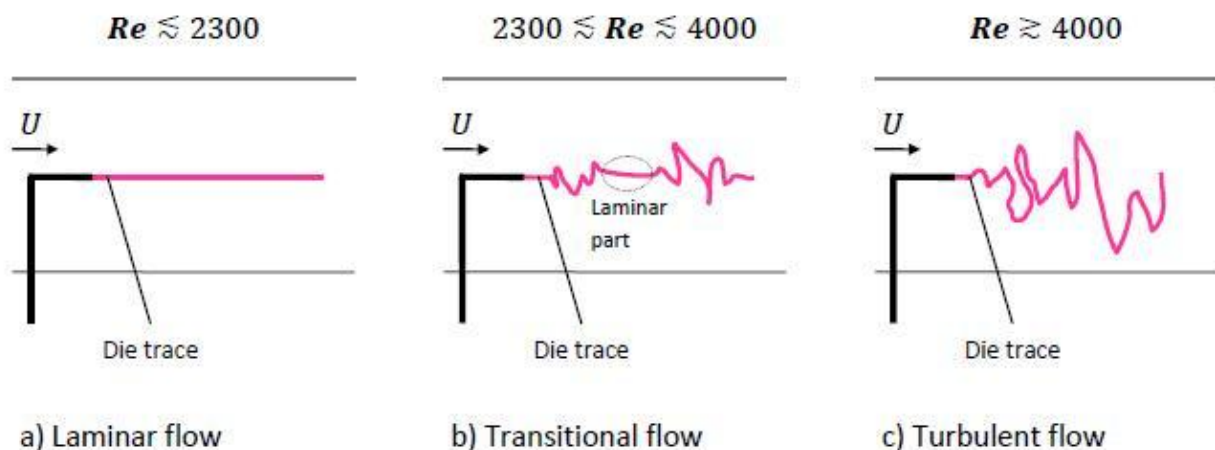
Figure A-34: Visualization of flow types under different Reynolds number intervals

A.5.4.3 *Major and minor losses*

Fluids energy per unit weight can be expressed as head. This concept relates the energy in an incompressible fluid to the height of an equivalent static column of that fluid. Head is abbreviated H, and total head is the sum of pressure head, potential head and velocity head. All these heads are derived from Bernoulli's equation (equation A.9).

$$\frac{p}{\rho} + \frac{u^2}{2} + gz = constant \qquad (A.9)$$

where:
p = pressure
g = acceleration
z = height

Major losses
The energy loss per length of pipe is associated with major losses, and is typical for systems with long pipes. The equation most commonly used to calculate major head is the Darcy-Weisbach equation A.10 given below.

$$h_f = f \frac{L}{D} \frac{U^2}{2g} \qquad (A.10)$$

Minor losses
Fittings, valves, bends, inlets, exits, expanders and reducers are contributing to minor losses, which normally dominates in short pipe systems with additional components. A dimensionless coefficient K_L, is used to express minor losses, which is given in equation A.11 below.

$$K_L = \frac{h_L}{U^2 \; 2g} \qquad (A.11)$$

where:
h_L = minor head loss, defines as equation A.12:

$$h_L = \frac{\Delta p_L}{\rho g} \qquad (A.12)$$

where:
Δp_L = pressure drop across the component.

By rearranging equation X-X above, equation A.13 is given:

$$h_L = K_L \frac{U^2}{2g} = \frac{\Delta p_L}{\rho g} \qquad (A.13)$$

B APPENDIX – TEST MATRISE

Figure A-35 below shows the testing parameters for each test that was conducted.

Screening retention time lab8

Test	Date	Time	Water (°C)	Q Pump (m³/h)	dP Pumps (bar)	Pol [PPM]	Viscosity (Pa*s)	Viscosity (Pa*s)	Viscosity (Pa*s), average	Power (Hz)	Comment
Pol-1	28.05.13	08:30:00	20	0	0	1000	1,520	1,38	1,4500		Pump Char.
Pol-2	28.05.13	08:55:00	20	0	0	1000	1,34	1,37	1,3550		Pump Char.
Pol-3	28.05.13	09:20:00	20	0	0	1000	1,39	1,36	1,3750		Pump Char.
Pol-4	28.05.13	10:05:00	20	1000	0	1000	1,5	1,36	1,4300	89	Pump Char.
Pol-5	28.05.13	10:25:00	20	1000	5	1000	1,34	1,36	1,3500	89	Pump Char.
Pol-6	28.05.13	10:45:00	20	1000	10	1000	1,36	1,44	1,4000	89	Pump Char.
Pol-7	28.05.13	11:10:00	20	1000	15	1000	1,33	1,35	1,3400	89	Pump Char.
Pol-8	28.05.13	11:30:00	20	1000	20	1000	1,37	1,36	1,3650	89	Pump Char.
Pol-9	28.05.13	12:15:00	20	200	0	1000	1,32	1,36	1,3400	18	Pump Char.
Pol-10	28.05.13	12:35:00	20	200	5	1000	1,37	1,36	1,3650	18	Pump Char.
Pol-11	28.05.13	13:00:00	20	200	10	1000	1,38	1,34	1,3600	18	Pump Char.
Pol-12	28.05.13	13:20:00	20	200	15	1000	1,36	1,36	1,3600	18	Pump Char.
Pol-13	28.05.13	13:40:00	20	200	20	1000	1,38	1,34	1,3600	18	Pump Char.
Pol-14	28.05.13	14:00:00	20	600	0	1000	1,38	1,36	1,3700	53	Pump Char.
Pol-15	28.05.13	14:15:00	20	600	5	1000	1,38	1,35	1,3650	53	Pump Char.
Pol-16	28.05.13	14:25:00	20	600	10	1000	1,36	1,37	1,3650	53	Pump Char.
Pol-17	28.05.13	14:55:00	20	600	15	1000	1,5	1,39	1,4450	53	Pump Char.
Pol-18	28.05.13	15:15:00	20	600	20	1000	1,35	1,35	1,3500	53	Pump Char.
Pol-19	29.05.13	08:10:00	20	0	0	1000	1,42	1,35	1,3850		A, new tank
Pol-20	29.05.13	08:20:00	20	0	0	1000	1,28	1,51	1,3950		A, new tank
Pol-21	29.05.13	13:30:00	20	200	1,79	1000	1,16		1,1600	18	A, 6mm
Pol-22	29.05.13	13:50:00	20	400	4,24	1000	1,23		1,2300	35	A, 6mm
Pol-23	29.05.13	14:10:00	20	600	7,47	1000	1,28		1,2800	53	A, 6mm
Pol-24	29.05.13	14:25:00	20	800	11,4	1000	1,19		1,1900	71	A, 6mm
Pol-25	29.05.13	14:40:00	20	1000	16,27	1000	1,17		1,1700	89	A, 6mm
Pol-26	29.05.13	14:50:00	20	200	0,41	1000	1,28		1,2800	18	A, 8mm
Pol-27	29.05.13	15:00:00	20	400	0,92	1000	1,26		1,2600	35	A, 8mm
Pol-28	29.05.13	15:10:00	20	600	1,59	1000	1,27		1,2700	53	A, 8mm
Pol-29	29.05.13	15:20:00	20	800	2,42	1000	1,24		1,2400	71	A, 8mm
Pol-30	29.05.13	15:30:00	20	1000	3,24	1000	1,26		1,2600	89	A, 8mm

Screening retention time lab8

Test	Date	Time	Water (°C)	Q Pump (m³/h)	dP Pumps (bar)	Pol [PPM]	Viscosity	Viscosity	Viscosity	Power (Hz)	Comment
Pol-31	29.05.13	16:15:00	20	200	0,21	1000	1,25		1,25	18	A,10mm
Pol-32	29.05.13	16:30:00	20	400	0,4	1000	1,26		1,26	35	A,10mm
Pol-33	29.05.13	16:40:00	20	600	0,64	1000	1,25		1,25	53	A,10mm
Pol-34	29.05.13	16:50:00	20	800	0,91	1000	1,25		1,25	71	A,10mm
Pol-35	29.05.13	17:00:00	20	1000	1,18	1000	1,26		1,26	89	A,10mm
Pol-36	29.05.13	17:15:00	20	200	0,12	1000	1,39		1,39	18	A,12mm
Pol-37	29.05.13	17:25:00	20	400	0,19	1000	1,24		1,24	35	A,12mm
Pol-38	29.05.13	17:35:00	20	600	0,27	1000	1,24		1,24	53	A,12mm
Pol-39	29.05.13	17:45:00	20	800	0,38	1000	1,26		1,26	71	A,12mm
Pol-40	29.05.13	17:55:00	20	1000	0,48	1000	1,25		1,25	89	A,12mm
Pol-41	29.05.13	18:05:00	20	200	0,1	1000	1,25		1,25	18	A,15mm
Pol-42	29.05.13	18:15:00	20	400	0,13	1000	1,26		1,26	35	A,15mm
Pol-43	29.05.13	18:25:00	20	600	0,18	1000	1,25		1,25	53	A,15mm
Pol-44	29.05.13	18:35:00	20	800	0,22	1000	1,26		1,26	71	A,15mm
Pol-45	29.05.13	18:45:00	20	1000	0,28	1000	1,27		1,27	89	A,15mm
Pol-46	30.05.13		20	0	0	1000					Tank viscosity
Pol-47	30.05.13		20	0	0	1000					Tank viscosity
Pol-48	30.05.13		20	400	20	1000					High bar, std
Pol-49	30.05.13	13:20:00	20	0	0	1000	1,32		1,32		Tank viscosity
Pol-50	30.05.13	13:30:00	20	400	0	1000	1,2		1,2		High bar, std
Pol-51	30.05.13	13:40:00	20	400	5	1000	1,12		1,12	53	High bar, std
Pol-52	30.05.13	13:50:00	20	400	10	1000	0,534		0,534	53	High bar, std
Pol-53	30.05.13	14:00:00	20	400	15	1000	0,356		0,356	53	High bar, std
Pol-54	30.05.13	14:15:00	20	400	20	1000	0,273		0,273	53	High bar, std
Pol-55	31.05.13	08:25:00	20	0	0	1000	1,33		1,33	53	Tank viscosity
Pol-56	31.05.13	08:35:00	20	1000		1000	1,28		1,28	89	8mm
Pol-57	31.05.13	08:45:00	20	800		1000	1,28		1,28	71	8mm
Pol-58	31.05.13	08:55:00	20	600		1000	1,28		1,28	53	8mm
Pol-59	31.05.13	09:10:00	20	400		1000	1,31		1,31	35	8mm
Pol-60	31.05.13	09:30:00	20	200		1000	1,35		1,35	18	8mm

Screening retention time lab8											
Test	Date	Time	Water (°C)	Q Pump (m³/h)	dP Pumps (bar)	Pol [PPM]	Viscosity	Viscosity	Viscosity	Power (Hz)	Comment
Pol-61	31.05.13	09:50:00	20	1000		1000	1,23		1,23	89	8mm+coil
Pol-62	31.05.13	10:00:00	20	800		1000	1,33		1,33	71	8mm+coil
Pol-63	31.05.13	10:10:00	20	600		1000	1,29		1,29	53	8mm+coil
Pol-64	31.05.13	10:20:00	20	400		1000	1,28		1,28	35	8mm+coil
Pol-65	31.05.13	10:30:00	20	200		1000	1,3		1,3	18	8mm+coil
Pol-66	31.05.13	10:40:00	20	1000		1000	1,06		1,06	89	Std valve
Pol-67	31.05.13	10:50:00	20	800		1000	1,03		1,03	71	Std valve
Pol-68	31.05.13	15:00:00	20	600		1000	0,596		0,596	53	Std valve
Pol-69	31.05.13	11:10:00	20	400		1000	0,925		0,925	35	Std valve
Pol-70	31.05.13	11:20:00	20	200		1000	1,22		1,22	18	Std valve
Pol-71	31.05.13		20	0		1000					Std valve
Pol-72	31.05.13		20	1000		1000					Typhoon
Pol-73	31.05.13		20	800		1000					Typhoon
Pol-74	31.05.13		20	600		1000					Typhoon
Pol-75	31.05.13		20	400		1000					Typhoon
Pol-76	31.05.13		20	200		1000					Typhoon
Pol-77	31.05.13	12:20:00	20	1000		1000	1,21		1,21	89	Typhoon,new
Pol-78	31.05.13	12:30:00	20	800		1000	1,25		1,25	71	Typhoon,new
Pol-79	31.05.13	12:40:00	20	600		1000	1,27		1,27	53	Typhoon,new
Pol-80	31.05.13	12:50:00	20	400		1000	1,29		1,29	35	Typhoon,new
Pol-81	31.05.13	13:00:00	20	200		1000	1,35		1,35	18	Typhoon,new
Pol-82	31.05.13	13:20:00	20	1000		1000	0,867		0,867	89	Std valve
Pol-83	31.05.13	13:30:00	20	800		1000	1,12		1,12	71	Std valve
Pol-84	31.05.13	13:50:00	20	600		1000	1,23		1,23	53	Std valve
Pol-85	31.05.13	14:00:00	20	400		1000	1,27		1,27	35	Std valve
Pol-86	31.05.13	14:10:00	20	200		1000	1,27		1,27	18	Std valve
Pol-87			20								
Pol-88			20								
Pol-89			20								
Pol-90			20								

Figure A- 35: The test matrise for the different tests