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Abstract

Foamed cement has become a well established cementing method for many applications in oilwell cementing all over the world.

A key factor to a successful foam cement job is an optimized cement slurry design. To achieve optimal slurry design the project engineer is working in close collaboration with the onshore cement laboratory. In laboratory testing, the foam stability is an important factor. In recent years it is claimed that the foam stability results from the cement laboratory seems not to fully match with the actual results in the field. The experience is that slurries seem to be somewhat more stable in the field than in the laboratory.

Today, laboratory foam cement is created in a closed blender according to ISO 10426. The main focus in this thesis is to investigate a new way of creating foam cement in the laboratory approaching a replicated, downscaled model of the method that is used in the field.

An open, atmospheric flow loop was designed and built with a tee shaped construction joint for nitrogen injection to resemble onsite foam generation. The results showed that the foam generator loop was able to create foam, but the bubble size was significantly larger compared to the laboratory closed blender foaming process. Hence a good deal of improvement of the prototype is required.

Acknowledgements

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1. Introduction

This thesis focuses on the methodology of creating foam cement in laboratory conditions.

Cementing has been used in oilwell drilling since early 20th century. It has become a very important factor to achieve good integrity of an oilwell. A bad cement job can lead to hazardous situations, and shorten the lifetime of the well.

Foam cement is a lightweight cement solution that has become widely used all over the world. It consists of base cement slurry, a surfactant and a gas. Foam cement is a brilliant solution for wells for a number for reasons, usually for lowering density. Excellent mud displacement, enhanced mechanical properties, good strength-to-density ratio and long lasting zonal isolation are some of the advantages. The possibility of changing the density up to last minute also gives a good flexibility in addressing unexpected downhole conditions.

In all oilwell cementing operations, the laboratory testing is an essential contributor to a successful result. Variations in cement batches and chemicals make the need for testing with relevant samples very important. In foam cementing the stability of the foam is one of the most important contributors to a successful result. Therefore a good result from the laboratory testing is very important and gives a good indication of how the cement will behave offshore. In some cases these results do not compare well with the offshore results. There are examples that foaming ability and foam stability in laboratory conditions, seems not to fully match with the actual results in the field. This is also the experience from previous work .[1] This is most likely because the foaming process offshore produces much better mixing energy, and smaller and better dispersed bubbles than the current laboratory method.

Today laboratory foam cement is generated in a closed multiblade blender according to ISO 10426-4 specifications. In the field, foam cement is created by injecting nitrogen at high pressure into a pre-mixed cement slurry flow in a designated foam generator.

The main focus of this thesis is to investigate a different technique of foaming the cement in laboratory conditions that is more similar to the offshore method and if this principle is possible to be used under atmospheric pressure.

2. Theory

2.1. What is Oilwell Cementing?

Well cementing has been used for nearly a century and the first well where cement was used to shut off downhole water was in 1903. The two plug cementing method was introduced by A.A. Perkins in 1910. It was this method that made up the modern way of oilwell cementing. [2]

"Production optimization begins with a good completion and a good completion depends on the integrity of the primary cement job." This is how Carl T. Montgomery starts the first chapter in Well Cementing and gives a good view of the importance of a good cement job.[3]

Oilwell cementing is usually divided into two main categories, primary and remedial cementing. Primary cementing is when the cement slurry is pumped down inside the casing and placed in the annulus between the casing and the formation exposed to the wellbore. Since the first cement job, the main purpose primary cementing should isolate oil, water and gas zones from each other and from surface. It could be that an oil zone needs to be isolated from another oil zone. To be able to do this sealing job, the bond between the cement and the casing and between the cement and the formation has to be adequate. Preventing fluid channeling is also an important objective, and therefore proper annular fill is required. These important objectives make the primary cement jobs of a well one of the most important operations performed in a well. If the cement jobs in one well is poorly performed, this could prevent the well from producing it`s whole potential. But more importantly it can cause severe risks for unwanted loss of well control.

Remedial cementing can be divided into two main categories, squeeze cementing and plug cementing. Squeeze cementing is the operation where the cement is placed into the wellbore and hydraulic power is used to squeeze the cement into flow paths that wants to be shut off. In this operation, the cement slurry is partially dehydrated which makes the cement harden and seal all voids. Plug cementing is to place a volume of cement inside the wellbore at a specific location to seal off the wellbore. [2]

An oilwell cement job is strongly influenced by cement slurry density. In weak formations the required cement density can be quite low, less than 1.5 SG. (Specific Gravity). To get stable slurries with sufficient strength in this density region, there are some alternatives to conventional cementing.

2.2. Lightweight cementing

Lightweight cementing is required in many cases with low fracture gradient and can be performed in many ways. One of the options is to use a light conventional slurry design, which means a slurry without any unusual additives other than extenders. The challenge of conventional slurry design could be achieving sufficient compressive strength and adequate mechanical properties, often in terms of compressive strength. In order to obtain better compressive strength, some techniques have been developed. This includes various hollow microsphere cement additives and foamed cement applications.

One of Halliburton`s light weight cement option is called Tuned Cementing Solutions™(TCS) and has several benefits compared to conventional design. It is a non-foamed microsphere cementing system designed to meet specific wellbore performance requirements. To get a lighter cement slurry, hollow microspheres are used. This gives a benefit in which the water ratio can be lowered to increase the early strength development and final strength. Compared to foam cementing, TCS can be used where foam cementing is not possible due to logistic issues or the operator does not want energized fluid in the well. [4]

The other light weight solution is foam cement, which this thesis is focusing on.

2.3. What is Foam Cement?

Foam cement is a lightweight cement slurry, containing cement slurry, a foaming agent and a gas. When these ingredients are properly mixed together, it forms an extremely stable, lightweight cement slurry that looks like gray shaving cream. The slurry contains small, generally microscopic, bubbles that will not coalesce or migrate. The challenge is to get the bubbles small and uniform, to prevent them from coalescing and migrate upwards. This will, if successful, make the foam cement low permeable and relatively high strength. The technology of foam cementing has been used for many decades in the petroleum industry. The main aspect of using it is to get the slurry density down and be able to adjust the slurry density by adjusting the nitrogen amount. In the last decade foaming has also been applied to modify the mechanical properties even if light weight is not required. [5]

There are several benefits using foam cement compared to hollow microsphere systems. Hollow microsphere system needs a pre-mixed cement blend brought out to location, while foam cement can use standard well cement. A pre-mixed cement blend does require extra storage capacity which can be a problem when large volumes are needed.

2.4. Why and where is foam cement used?

The foam cement technology can be considered in most cement job operations all over the world, onshore and offshore. Foam can be used on remedial and primary cement jobs, even if the well is horizontal. Although the foam operations can be very complex, foam cement has many applications that can justify the increased complexity.

Claimed benefits for foam cement:

- *Lightweight*
  If lightweight cement has to be used in the well, foam cement will secure a stable lightweight cement columns in annulus. Cement can be foamed down to 480 kg/m^3 in some cases. It is worth mentioning that mud, spacer and preflushes also can be foamed to desired density.
- *Elasticity and mechanical properties*
  Elasticity and mechanical strength are the most crucial properties for long-term zonal isolation. Foam cement exhibit improved ductility over conventional cements. This allows the foam cement to withstand higher hoop stresses from casing pressure and temperature cycling. This leads to lasting zonal isolation that means no sustained casing pressure, less produced water, fewer workovers and more efficient production.
- *Mud removal*
  Due to the high apparent viscosity and two-phase composition of the foam cement, the mud removal is substantially better than for conventional slurry cementing. The viscosity increases the bubble concentration increases, so a higher foam quality will give better mud removal in most cases.
- *Energized*
  Foam cement expands if the borehole has washouts or zones that has experienced lost circulation.
- *Prevents gas migration*
  The nitrogen bubbles helps maintaining pressure and prevent shrinking when the cement is hydrating which helps prevent gas influx or water influx.

- *Good zonal isolation*
  The capability of expanding gives very good zonal isolation and foam cement is found to give excellent bonding between casing-cement and formation-cement.
- *Insulates*
  The bubbles in the cement give a low thermal conductivity which gives good insulation. That could be a benefit when cooling is undesired.

<u>Example from cyclic stress test:</u>

This picture shows sections from a cyclic stress test. In each test cement was allowed to cure, after which the internal casing was pressurized to simulate actual well conditions. The conventional high strength neat cement to the left in figure 1, failed when the internal pressure reached 4.500 psi. When foam cement was tested in the same way, in maintained integrity when cycled to more than 9.000 psi. This shows the significance of foam cementing. [6]

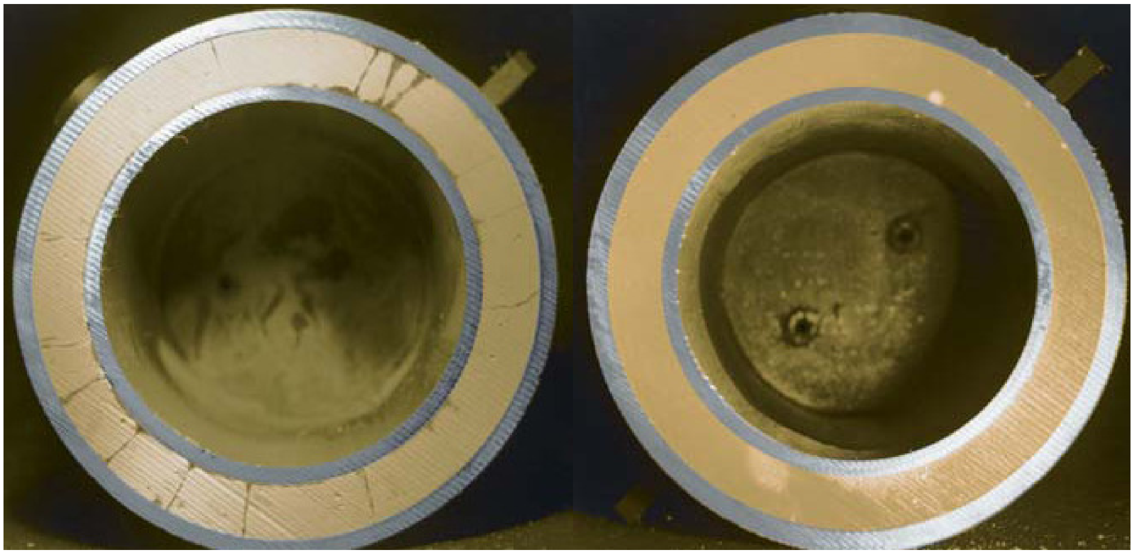

Figure 1:Left picture is conventional cement and right picture is foam cement.[6]

2.5. How is foam cement made in the field?

Foam cement is generated from a base cement slurry, foaming agent and nitrogen. These components need to be mixed together properly and in the right order.

The mixing of foam cement starts in the cement mixing unit, where the base slurry is mixed at a predefined rate and density. This cement unit is the same unit that is used for conventional cement jobs.

When the base slurry leaves the cement unit the foamer/stabilizer is joined with the cement flow in a line from the foamer/stabilizer injection skid. This typically is done on the suction side of the high pressure pumps used for the job. Then the mixture flows towards a foam generator manifold.

The foam generator is where the nitrogen and the base slurry containing foamer meet. The foam generator itself is constructed as a tee junction. The nitrogen comes in horizontally and meets the cement flow which comes in from above, vertically. The nitrogen is injected at high pressure drop in order to get enough energy to create stable foam as the foam progresses through a straight section in the foam manifold. Thereafter the foamed slurry is pushed down hole. The principle is showed in figure 2 below.

The pump rate of nitrogen is closely monitored and matched up with the base slurry rate to get the right ratio. Because of higher pressure at the bottom of the well than higher up, the amount of nitrogen has to be adjusted during the foam cement job to get the right density in all sections of the well.

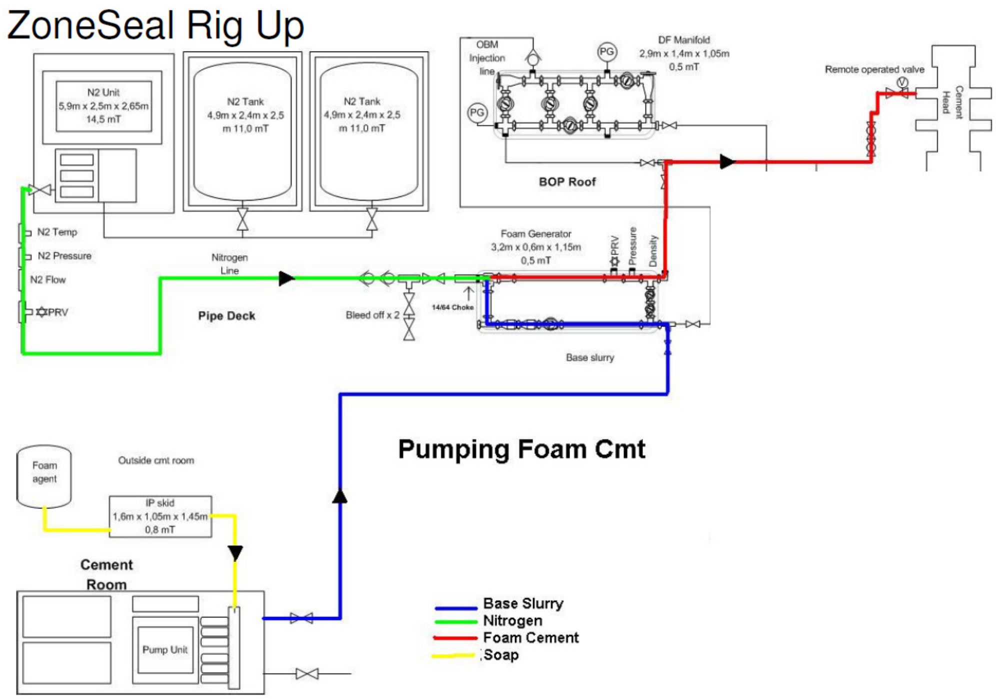

Figure 2: Halliburton ZoneSeal Rig Up, Halliburton AS[5]

2.6. Components in field rig up

The foam cement field rig up, hereafter called ZoneSeal Rig Up is assembled of many parts. In this section every one of them is described. The cement unit that mixes the cement is not considered in this part.

2.6.1. Cement Pump

The pumping unit that is used is a HT-400 triplex pump made by Halliburton. The pump is usually fit into the cement unit that is mixing the cement slurry for each job.

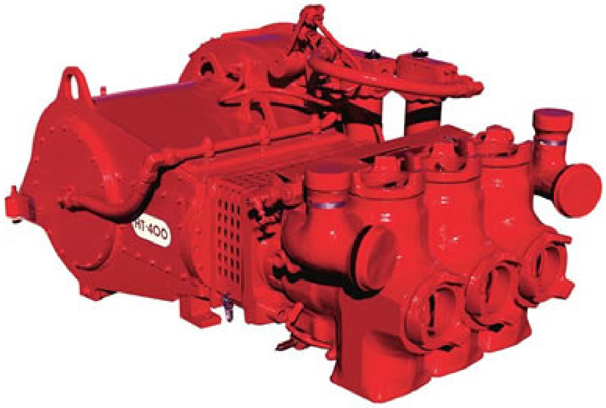

Figure 3: Halliburton HT-400 pump, Halliburton AS

2.6.2. Foam Tee Generator

The offshore foam generator consists of a standard high-pressure hammer-union tee with a choke holder nipple and a ceramic choke. The choke is replaceable and is available in many different sizes. The sizes are classified in X/64”, so every step counts 1/64” in size. This gives the engineer the opportunity to change the choke size relatively fast in order to get the right choke size for the actual job. Usually this choke size is predetermined in the planning phase of the foam cement job.

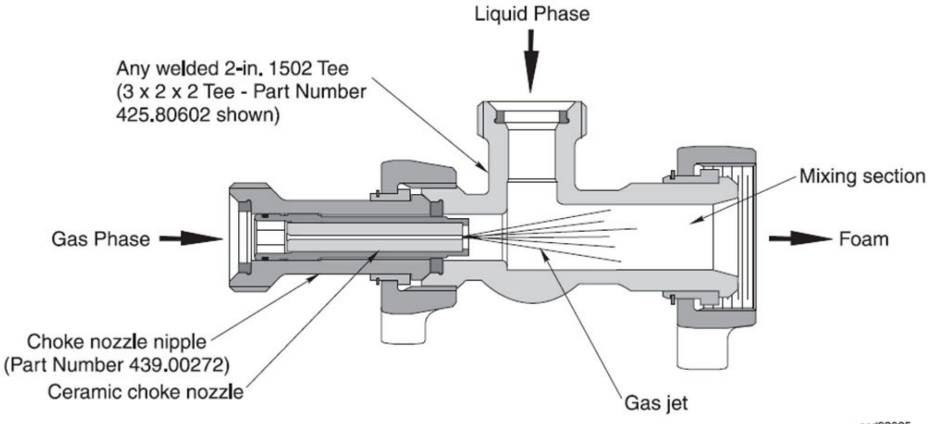

Figure 4: Hammer Tee Union with Choke Nozzle[5]

2.6.3. Nitrogen Injection System

The nitrogen is injected at a predefined high pressure into the hammer union tee. The rate and pressure is predetermined and slaved by the flow rate from the cement unit. This is done to be able to monitor and adjust the downstream density of the foamed cement.

2.7. The basic principles of foams

When a fluid and a gas are mixed together properly and the gas phase becomes a cloud of bubbles that are dispersed in the fluid, foam has been formed. Foam has been of great practical interest because of their widespread occurrence in everyday life. In the everyday life we have a lot of foams around us, for instance foam rubber, shaving cream, fire extinguishing foams and many more. The foam has shown that it suits many other applications, including the petroleum industry. The use of foams in the petroleum industry may not be that familiar, but has been used for a long time for many applications. It is used in drilling mud, fracturing fluids, acidizing fluids and cementing.

Foam is a colloidal species where gas is dispersed in a continuous liquid phase. The term colloidal is referred to as a system of two separate phases. The dispersed phase is often called the internal phase and the continuous phase as the external phase.

In reality foam cement is a three-phase system because the liquid phase carries both a large concentration of solids and the gas bubbles. Generally the volumetric fraction of gas in these systems, typically 20-25 %, hence it can be debated if these systems should be called foams.

A foam structure can always be formed in a liquid if bubbles of gas are injected faster than the liquid between bubbles can drain away. Even if the bubbles coalesce as soon as the liquid between them are drained away, a temporary dispersion is formed. It is difficult to distinguish between stable and unstable foam, because no foams are thermodynamically stable. All foams will collapse after some time. In this case with foam cement the continuous phase solidifies and become a cement matrix.

Stability of foams is the property of which the bubbles stays in suspension and does not migrates upwards. As mentioned, no foams are thermodynamically stable, but in this term stable is meant as relatively stable in a kinetic sense. Hence, the stability means that the dispersed bubbles are held relatively balanced in the continuous phase. When we define foam stability, there are two different processes that is considered, film thinning and coalescence. The film thinning process is that two or more bubbles get close together. The material that separates them gets thin, but they are not touching each other. Coalescence is the process where two or more bubbles merge together and form a single, larger bubble. This reduces the total surface area and since the bubbles creates one large bubble; the bubble will rise faster, due to Stokes law.

In a pure liquid the dispersed gas bubbles will rise up and separate, more or less like in Stokes` law. The bubbles come together and coalesce almost instantly, with no sign of flattening between them, since there is no thin-film persistence. If the same foam was added a surfactant, thin-film stability between the bubbles would form and the bubbles would not coalesce that rapidly. This helps the foam stability. This describes the importance of a surfactant in foaming processes.

As mentioned, foam consists of a continuous and a dispersed phase. Between them there is a boundary region, called the interface. Interfacial properties are very important since the gas bubbles have a large surface area. This surface has a given surface energy per unit area. This means that to create foam a need of enough energy is desired. To illustrate this we can consider a constant amount of gas dispersed in water. Then the total surface area increases when the bubble size decreases. When we get more surface area, we get more surface energy. In the end we need more energy to produce smaller bubbles. If this energy cannot be provided through mechanical energy, surfactants can be added to lower the interfacial tension. Lowering the interfacial tension will lower the amount of mechanical energy needed for creating foam.

Surface tension has the unit of energy per unit area, which explains the fact that area expansion of the surface requires energy. Physically, surface tension is viewed as the sum of the contracting forces that act parallel to the surface or interface. To illustrate this principle, a classic figure is used that simplifies the surface of a bubble to a 2-dimensional illustration. The illustration demonstrates the work required to expand the surface against contracting forces is equal to the increase in surface free energy (dG).

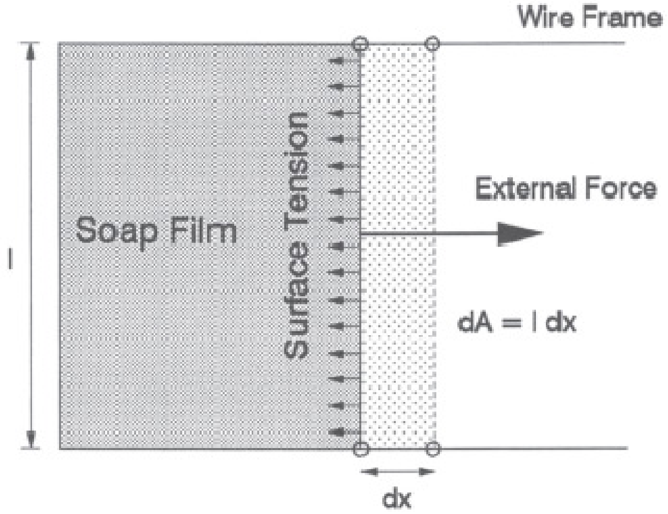

Figure 5: Surface tension, a surface-contracting force per unit length and a surface energy per unit area.[7]

The surface tension (γ°) and interfacial tension (γ) is defined as the contracting force per unit length (l) around a surface. From the illustration we get

$$work = \gamma° l dx = \gamma° dA$$

$$dG = \gamma° dA$$

Here the wire is moved a distance dx and the increase in area dA equals l times dx. The surface tension can be expressed as force per unit length or energy per unit area.

The pressure regimes in foams are also a important aspect. The interfacial tension of a bubble causes a pressure difference of the inside and the outside of the bubble. The interface between a gas phase G, in a bubble, and a liquid phase L, that surrounds the bubble, have the pressure P_G and P_L respectively. For spherical bubbles of radius R in wet foam, the equation that describes the pressure regime is:

$\Delta P = P_G - P_L$

$\Delta P = 2\gamma°/R$

This equation is the Young-Laplace equation and show that ΔP varies with the radius R of the bubble.

Overall, this theory emphasis that making smaller bubbles rquires more energy added to the system. In this thesis, that means that higher mechanical energy is needed in form of higher energy in the nitrogen jet. [7]

2.8. Foam cement design and composition

As mentioned foam cement contains base slurry, a foaming agent and a gas. In this section all three of them will be discussed.

When foam cement is described an often used term is *foam quality.* This term describes the volume of gas relative to the total volume of foam. For instance, a 25 % quality implies that there is a volume of 25 % gas in the total volume of foam. This term is used very frequently when all types of foam are described.

The pressure regime in a planned foam job is a very important factor to success. In all well cementing, the pressure in different parts of the well will vary. The pressure at the casing shoe will for instance be larger than higher up in the well. Because of this, the nitrogen injection rate has to be adjusted continuously or stepwise during a foam cement operation.

2.8.1. Base slurry

Before a base slurry design can be decided, the desired foam quality and density has to be defined. The required foam density and quality are strongly influenced by the type of job. Usually the range of foam quality is kept between 18-28 %, because a higher quality can cause coalesce of the bubbles and cause excessive permeability. If the foam density is pre-determined, the base slurry density can be calculated. This is depending on the purpose of the foam cement job. One important issue is that the same mechanisms that cause free water also contribute to segregation in foamed slurries.[1] In other words, unstable base slurry is not a good starting point for a foam slurry design. On the contrary, highly stable and viscous base slurry is necessary.

2.8.2. Foaming agents and stabilizers

There are quite a few foaming agents used in foam cementing, but on the Norwegian continental shelf only a small number of them are allowed. This is due to the environmental restrictions in Norway.

To create stable foam a foaming agent and a foam stabilizer are needed. Therefore often a combined foaming agent and stabilizer are used. This is to make it easier to handle, since only one liquid is then used.

2.8.3. Nitrogen chemistry

Nitrogen is the most used and preferred gas for foam cement jobs. Compressed air is also used in some cases, but in Norway only nitrogen is used. Air can be cheaper than nitrogen, but could be a problem when high volume, rate and pressure are required for enough mixing energy.

The two main reasons for using nitrogen instead of air are that nitrogen is an inert gas and is relatively cheap. These two properties are the main reason for that Halliburton is using nitrogen in its field infrastructure.

Nitrogen is the main component of the air in our surroundings, which contributes to its relatively low price. It is liquefied by compression, heat removal and expansion, repeated over and over again until the gas becomes a liquid.

2.9. Laboratory Testing of Foam Cement

Most of the testing needed for foam cement design can be done in laboratories. The testing is normally done at atmospheric pressure, since dealing with high pressure foam is problematic.

Foamer and stabilizer are used in relatively small volumes and are essentially benign. The other chemicals and cement are also benign and well suited for testing in laboratory conditions.

To be sure that the cement design is appropriate for the given cement job, laboratory testing is essential. Generally, the nitrogen used in foam cementing does not react chemically with the slurry. Therefore most of the testing of the base slurry in the laboratory generally is executed without using nitrogen.

In general, the ISO 10426-2 standard is used for all laboratory well cement testing. The dry cement water and chemicals are weighted to right amount and the water poured into a standard blender. The blender is started at 4000 rpm and the chemicals and cement are added within 15 seconds. Then the mixing speed is increased to 12000 rpm in 35 seconds. Then the cement slurry is ready for wanted testing.

The laboratory cement slurry testing can be very complex as there are many parameters that should be tuned to the right specifications. As an example, if foam cement slurry has low rheological properties and at the same time the thickening time is too short, an increased amount of retarder is needed. This will in many cases give an even lower viscosity and has to be accounted for by adding a chemical to increase the viscosity.

2.9.1. Foam Capability

This test is done according to the ISO 10426-4, Preparation and testing of Foamed Cement Slurries at Atmospheric Pressure, also called ANSI/API Recommended Practice 10B-4.[8]

Foam capability test is performed to check foamer/stabilizer compatibility if applicable, foaming capability and foam stability. The equipment required is a special foam cement blender with multiple blades. A measured amount of base slurry is placed in the blender and the right amount of foamer is added. Then the blender is spun in 15 seconds and if the total foam cement volume is filling the blender completely, the cement has successively foamed. If not, the slurry should be redesigned.

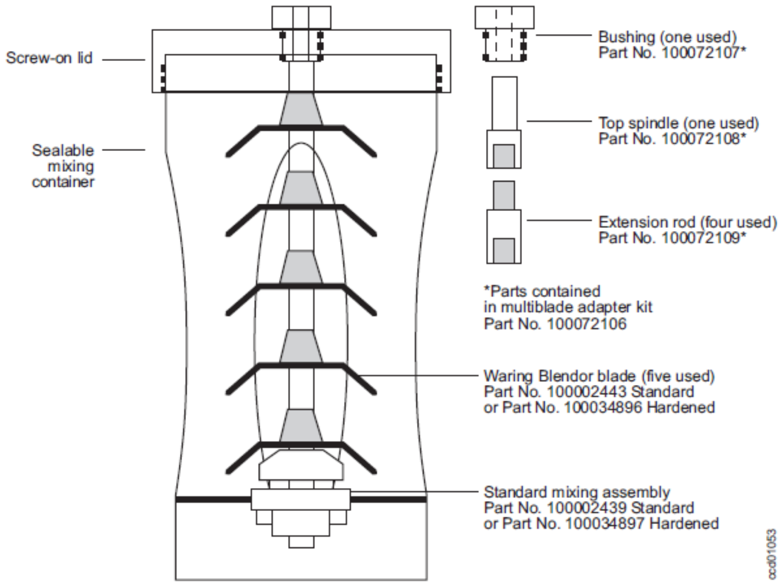

Figure 6: Multiblade blender for preparing atmospheric foam cement slurry.[9]

Foam slurry is poured into a large cylinder; 250 ml cylinders are often used. Then the stability and sink is measured to check if the foam has the needed stability properties. The sink determined by measuring how much the level in the cylinder has decreased. This is measured in millimeters (mm). The stability of the foam slurry is measured by taking samples from the top and the bottom of the cylinder. The sample is poured into a small cup with a predetermined volume and the weight of it is compared to the weight of water to find the density. If the density of the top and bottom are the same, the foam slurry is stable. The results are used to take a decision if the slurry design is good enough for the actual cement job.

2.9.2. Thickening Time

Thickening time testing is important to determine the viable pump time of the slurry using the given temperature and pressure schedule for the actual job. Temperature and pressure schedule are pre-calculated using either API schedule or simulation tools. The thickening time test is continuously monitoring the evolution of the consistency of the slurry according to the API 10B-2 procedure.

The unit of measurement for consistency is the Bearden unit of consistency (Bc) which is a dimensionless quantity with no direct conversion factor to more common units of viscosity.

The test is performed by a HTHP consistometer that is capable of ramping the temperature and pressure as predefined. Thickening time can be controlled by adjusting the amount of retarder in the slurry. There are retarders that are well suited for foam cement slurries.

Since the nitrogen is chemically inert, the thickening time generally is based on unfoamed slurry. The cement slurry is premixed conventionally, and the surfactant and foamer are added and carefully mixed in with a spatula. The whole slurry is then poured into a standard thickening time testing cup.

2.9.3. Rheology

Rheology of foam cement slurries is a very important parameter to know if the slurry design has the viscosity properties required. Adequate viscosity to hold the foamed slurry stable is essential to get a good foam cement job. The base slurry is therefore tuned to obtain the desired rheological properties. This is done by using a Fann 35 viscometer and measuring the rheology on room temperature and BHCT (Bottom Hole Circulating Temperature), with and without foamer.

Rheology of foamed cement can also be done. This normally done by a standard Fann 35 viscometer, but a FYSA (Fann Yield Stress Adapter) is preferably used to directly measure the yield point and also obtain better readings at low shear. The traditional bob/sleeve rheology relies on statistical regression of shear stress vs. shear rate. For foamed slurry the problem with the bob/sleeve is that the shear stress between the bob and the sleeve is not sufficient, which results in lower torque readings. Wall slippage is also a problem when using the conventional bob and sleeve, even for conventional slurries. This phenomenon is observed to be even greater for two-phase fluids as foamed cement. The FYSA is designed to minimize this problem. [10]

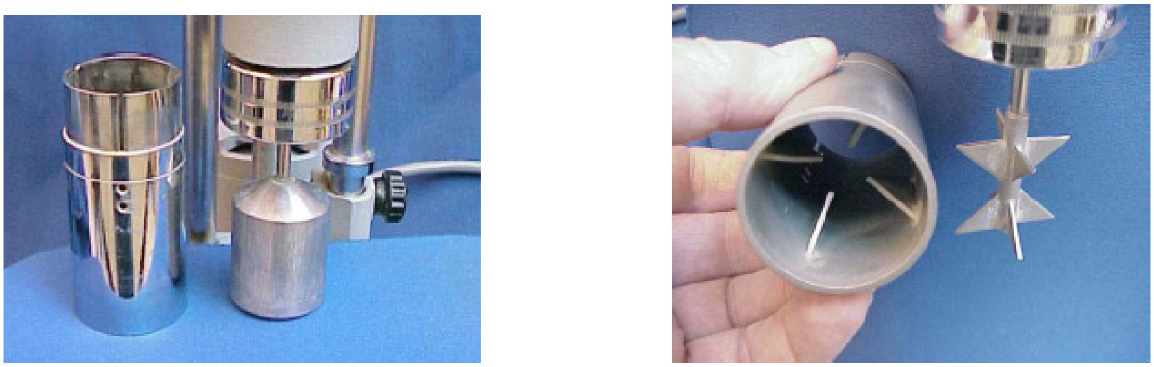

Figure 7: Standard bob and sleeve to the left and FYSA viscometer device to the right.[10]

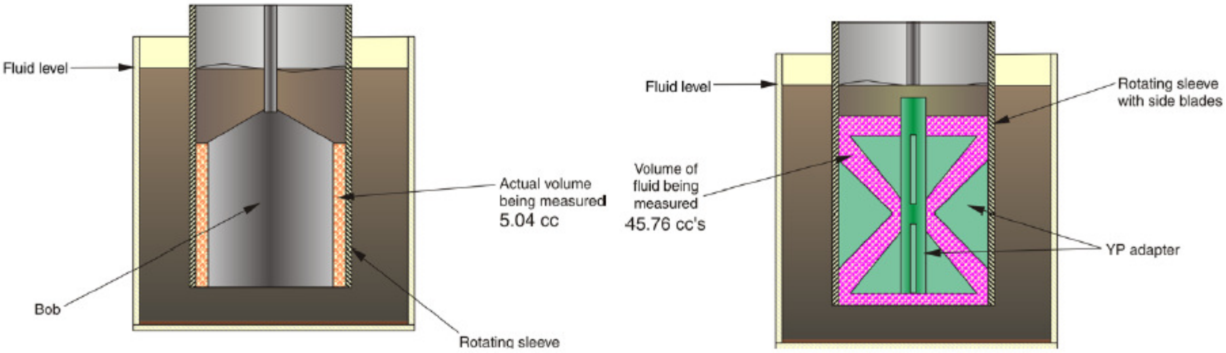

Figure 8: Standard bob and sleeve to the left, and FYSA viscometer to the right.[10]

2.10. Factors that can affect foam cement properties and stability

Stable foam is depending on many factors. To be able to better understand and improve foam cement testing, the factors that can affect the properties must be examined. Variations in slurry properties can have a major impact on the foam stability.

2.10.1. Specific mixing energy

When mixing a cement slurry, the mixing speed and mixing time can be varied. Laboratory mixing of cement has a recommended practice by ISO 10426-2 that is very precise and predefined. This procedure specifies what kind of blender that has to be used, mixing speed and duration time. The paper by Orban et al 1986[11], is focusing on the difference between this predefined method and the mixing done in the field. Their conclusion is that the properties of the cement slurry vary a lot with the intensity of the mixing. Especially rheologies, free water and fluid loss tend to vary. The reason for this seems to be connected to a deflocculating process, due to mechanical stresses during mixing phase. Although the paper concludes that optimum cement quality is obtained with the mixing energy close to the corresponding ISO 10426-2 laboratory procedure.[11]

This subject has also been discussed in papers[12] and shows that adding enough mixing energy is important. This can be even more important for a successful foam cement operation, since variations in base slurry properties can affect the foam stability and behavior.

The testing shows that the important area is when the dry additives are added to the mixing water. Lack of sufficient cement particle wetting efficiency when mixing can lead to variable slurry performance. If the slurry is properly mixed, the paper concludes that further batch mixing does not appear to appreciably affect measurable properties, as thickening time, fluid loss and free water/settling.[12]

A paper by Paul Padgett[13] also looked into this mixing energy questions. He concluded that the shear rate has much more influence on the cement slurry properties than the total mixing energy. He also concluded that the laboratory test equipment creates a much greater shear rate than the mixer used in the field. This shows that the cement slurry prepared in the laboratory is even better mixed than the slurry in the field.[13]

2.10.2. Bubble size and bubble size distribution

To create stable foam, the bubbles that are created are a very important factor to success. In these terms the Bubble Size Distribution (BSD) and the bubble size itself are often referred to. For the foam to be stable, the nitrogen bubbles needs to be held in suspension and not coalesce. There are several factors that can affect the bubble size and bubble size distribution.

The effects of bubble size and BSD in foams are widely discussed in papers. Many of these research papers describe the use of viscous fluid in the experiments conducted. In the paper “Bubble Size Distribution of Foam” the authors focus on the bubble size distribution and the effect of varying mixing speed in the mixer. They use a rotor-stator mixer and conclude that the mixing speed during foaming affects the bubble size. Higher speed makes smaller bubbles. The experiments were done with a non-solid fluid, but fine silica powder was added to study what happened when solids were involved. The results showed that the average bubble size decreased when the amount of silica increased. The results also showed that lower viscosity of the fluid caused larger bubbles. [14]

A fundamental problem with the current multiblade mixing method is that a large portion of the bubbles are generated very early in the mixing process, before high rpm is obtained, and hence they are larger than preferred and also not representative for the field foam generation. A reason to this could be insufficient mixing energy in the early start of the foaming process. The importance of enough mixing energy when generating foam is showed in the section 2.7.

The bubble rise velocity depends on the viscosity, μ and density, ρ of the fluid, and the size of the bubble. The viscosity and density are often characterized by the kinematic viscosity, ν which is the ratio between them. In non-Newtonian fluids, the gel development (thixotropicy) is also an important factor. Another challenge is the inability to sample and examine foam cement in the field at relevant conditions.

3. Laboratory Foam Cement Generator

3.1. Process of designing the foam cement generator

In order to better reflect the foaming principle done in the field, a small scale foam generator was planned to be build in the onshore laboratory. The main focus is to check if the principle of using compressed nitrogen as the foam creator can be used in this laboratory foam generator, so that the BSD reflecting offshore foam mixing can be made.

3.1.1. Previous work

In the laboratory the foam is generated in a closed blender where the foam occurs by mechanical forces, while the foam offshore is created by a nitrogen jet. To get the laboratory procedure closer to the offshore procedure, a small scale foam generator could be a solution. There are some earlier solutions to create foam cement in laboratory conditions which is described below.

In the paper by De Rozieres et al [1], a foam generator were created as a closed circuit. A base slurry and surfactant is added to the mixer. The foam is then created in a closed loop by the mechanical mixer and a piston moving up and down. This piston has a hole in it that transfers the slurry from one chamber to another. Proper amount of nitrogen is injected and as the slurry pumped back and forth between the chambers so the foam is created. When the slurry is properly foamed it is transferred to a test cell that was used under these experiments. This foam generator is operating as a closed circuit and therefore it could be pressurized. How this setup works in practice is not very thoroughly described, for instance the density and nitrogen injection measurements are not described in detail.

The Ph. D. thesis by Ali Mohsen Al-Mashat[15], also describes a foam cement generator which is used to create foam cement for rheological purposes. The system consists of a positive displacement plunger pump, a surfactant injection system and an air injection system. The rate of the cement and air is closely monitored to give wanted densities. The foam is created in a 12 " long steel pipe with 0.33 "ID filled with steel shavings to create the foam.[15]

Other papers are also using the standard foam blender described by API Recommended Practice 10B-4.

No other work has been found that creates foam using the same principle as Halliburton`s Foam Cement Generator in small scale laboratory testing.

3.1.2. The design process of the foam generator

As mentioned the goal of this thesis is to design a laboratory foam cement generator in the same principle as the large scale field foam generator. Therefore a mechanical mixer is not considered.

The main goal for laboratory testing onshore is to support offshore operations and make sure that the many slurry designs have the right specifications. In order to do that correctly, the same samples used on the rig have to be tested in the laboratory. To do that, the cementer at the rig has to take a sample of every component that is planned for the cement job and send them to shore by helicopter. This limits the amount of samples that can be sent in and usually around 10 kg of cement and 1 liter of each chemical is sent in. These samples are used during all testing for each rig; rheology, thickening time and UCA, and possibly foam cement properties. Therefore the generation of foam at the laboratory, cannot use unlimited volume of chemicals and cement, which implied that the foam generator had to be as small as practically possible.

The further work focused on how this foam generator should work and how complex it had to be. Since it was not sure that this small foam generator could produce proper foam, the decision was to make it as simple as possible in the first attempt.

To make it as simple as possible a loop design quickly came up. This would give us the opportunity to re-treat the slurry as it is pumped around in the loop. At the start it should have a tank that could serve as a reservoir to the loop`s pump. The pump had to be small and able to deliver at relatively low flow rates.

After the pump the foam generator had to be located. It was also planned as a tee construction with cement coming in from above and the nitrogen flow from the side of it in the further flow direction. As the field solution the tee was planned with a replaceable choke to vary the nitrogen flow. In order to make it solid and as close to the field foam generator it was found that it had to be custom made.

To be able to design the tee joint a suitable choke had to be found. The choke had to be available in different sizes and with a design that could be fitted into the tee joint. A small choke used in the industry for jet washers was found to be the best solution. It could be delivered down to 0.08 mm and up to 0.8 mm. After all the 0.08 mm choke had too long delivery time, so the smallest choke available was 0.12 mm. The foam generator was then designed to have the small choke fitted inside.

Adding pressure to the system could also be a relevant solution due to the pressurized system in the field rig up. If a closed, pressurized circuit had been chosen, the foam could not have been taken out in atmospheric conditions for evaluation. The bubbles would then be expanded and the foam quality would have increased significantly. One solution could be to have a test cell, for instance a HPHT foam stability cell in the circuit itself. Then the flow could have been shut off and the sample left in the cell when the cement had foamed. The idea was abandoned due to too high complexity and equipment needed for a high pressure circuit.

It was considered very important to find a pump that could work well for this application. It had to be relatively small and able to be run at flow rates down to 1-2 l/min. For future use it was desirable to get a pump that was powerful enough to deliver some pressure. It was also important to get a non-pulsating flow. The other objective was that cement flow consists of many particles that are able to get stuck or even plug mechanical parts, so the pump had to be relatively easy to clean. It was decided to focus on a pump that was robust and easy to clean, and at the same time delivering steady flow.

A membrane pump was discussed for its robustness, but not considered good enough because of too large pulsation. Centrifugal pumps were also discussed, but the sensitive mechanics was considered not to suit low flow rates and at the same time a constant flow. The third option was a peristaltic pump, which could be a good option since the fluid is just in contact with the hose and that makes it easy to clean. But the peristaltic pump was also considered to give too much pulsation during pumping. The pump that was finally chosen was the progressive cavity pump. This pump was considered to suit very well for the low flow rate and viscous flow of cement. The progressive cavity pump is quite easy to clean and gives an almost non-pulsating flow.

In order to get the volume of the loop as small as possible, the hoses was planned to be as small as possible. Since cement is a quite eroding material, high pressure hoses was chosen for the job. The dimension was set to ½” ID.

3.2. Final design of foam loop

As mentioned the foam generator was decided to be designed as a loop as shown in figure 9. The individual parts are described in chapter 3.2.

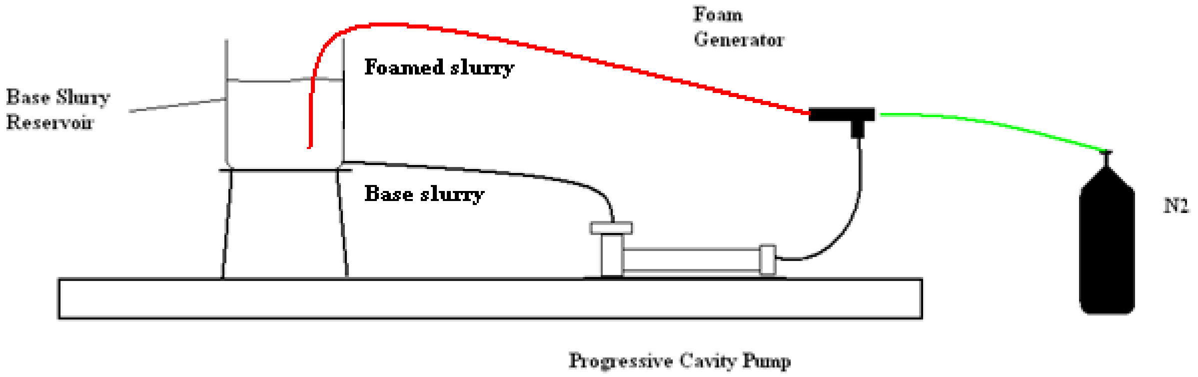

Figure 9: Final design of foam loop, schematic.

3.2.1. Pump

The pump used in the foam loop is a progressive cavity pump manufactured by Roto Pumps and delivered by Hillevåg Elektro-Diesel. The pump is one of the smallest that could be delivered in this pump category. The pump is also designed to withstand the erosion caused by cement flow.

Figure 10: Progressive Cavity Pump by Roto Pumps

3.2.2. Fittings and hoses

The fittings and hoses used in the foam loop are delivered by Mento AS. The hoses are single wall high-pressure hoses rated up to 105 Bar. The hose from the reservoir to the pump was 35 cm, from the pump to the foam generator was 50 cm and the return from the foam generator to the reservoir was 200 cm.

Figure 11: Foam Loop Hoses

3.2.3. Reservoir

The reservoir that should act as fluid supply for the loop is a steel tank with an outlet placed in the bottom floor. The reservoir is designed as an open tank, so the return flow could be routed back and into the bottom of the tank.

Figure 12: Foam Loop Reservoir

3.2.4. Choke

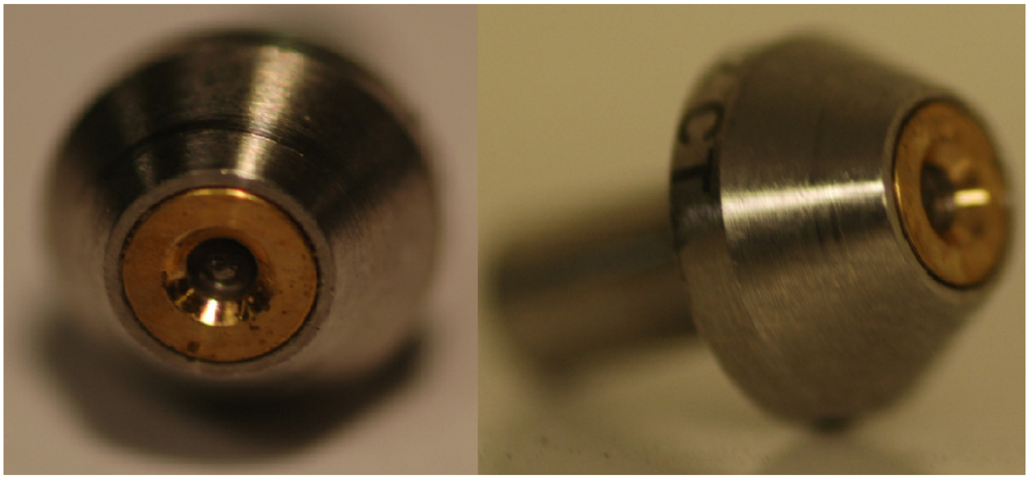

Figure 13: Foam Generator Choke

In the process of finding a suitable choke, many types were evaluated. The best option was a small ceramic choke called Saphire orifice with a collar at one end, as showed in figure 13 and 14. The choke is delivered by Storm-Halvorsen, Sandefjord. This choke is used in the industry for jet cutting and is rated for 4000 Bars.

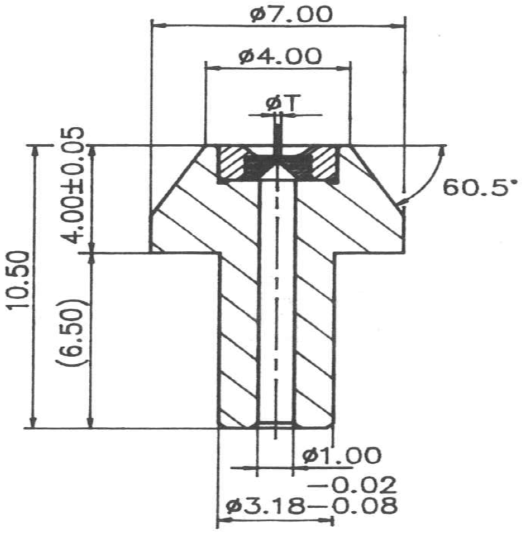

Figure 14: Jet Cutting Nozzle, flow direction from above, Storm Halvorsen AS

3.2.5. Foam generator tee construction

Before the foam generator tee construction could be designed and manufactured, the type of nozzle/choke had to be found to be sure the choke could easily be fitted into the joint. When the right choke was found, the final design of the tee joint could be manufactured. To build the foam generator tee Simplicity AS was contacted. It was then decided that Varhaug Maskinering AS could help making it. Since the upstream gas pressure is quite high, the tee had to be made of high quality steel. Figure 15 and 16 is showing the final design.

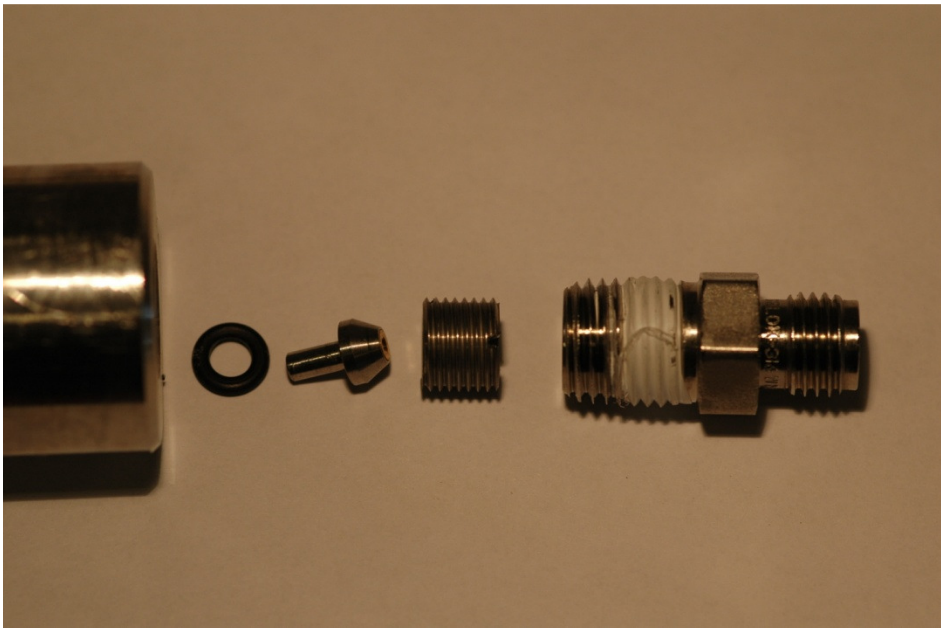

Figure 15: Showing how the choke is fitted into the foam generator

Figure 16: Foam Tee Generator with nitrogen supply connected.

4. Practical part

4.1. Assembling the foam generator loop

After receiving all the components for the foam generator loop, the assembling process could start. A suitable place for the foam generator loop was found in the laboratory and the pump was the first to be installed, which required an electrician. The pump with its motor was quite big so it determined how the other parts could be assembled. To make the hoses as short as possible, the reservoir had to be placed on a trolley in front of the pump. The final setup is shown is figure 17.

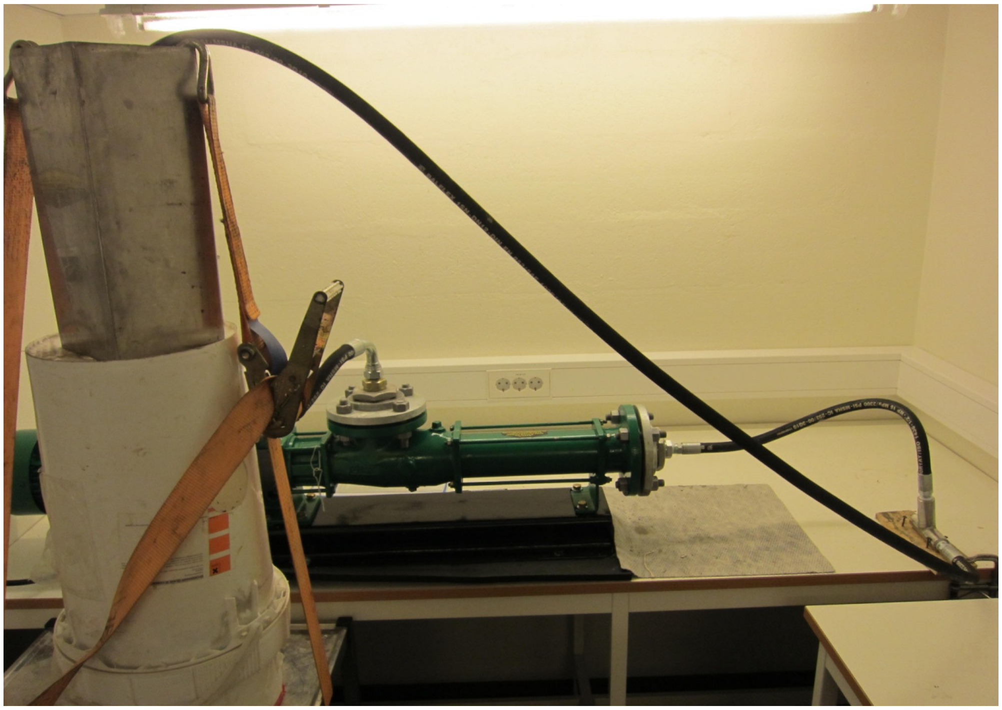

Figure 17: Final rig up of the laboratory foam generator loop.

4.2. Laboratory testing

In all this testing a standard foam cement recipe was used, as seen in table 1. The recipe was based on a surface casing foam cement job executed by Halliburton, but with no retarders added to make it less complex.

Surface Casing Foam Cement Recipe 1,70 s.g./14.187 PPG Foam quality wanted 21.56 %/Foamed down to 1.32 S.G.	
Material	**Concentration**
Cement DWFS	100 % BWOC
Foamer	4 % BVOW
Fresh Water	75.10 % L/100 kg

Table 1: Cement Slurry Recipe

This slurry design was then tested for Foam Capability, and the stability and sink was measured.

Sink [mm]	Time to foam [sec]	Average Mixing Speed [rpm]	Foam Density [SG]	SG top	SG bottom
3	10	7500	1.34	1.34	1.35

Table 2: Results from multiblade blender foaming according to ISO 10426-4

This result shows great foaming properties and almost 100 % stable foam as seen in table 2, even though the wanted density was 1.32 SG. Next step was to use the same recipe in the foam generator loop, to see if it could create stable foam and compare with the conventionally foam slurry.

4.2.1. Foam cement generator loop-testing

The 1.70 foam cement base slurry was mixed in a amount of 3000 ml using a large laboratory blender, to be sure to have enough for all testing. The foamer was added into the blender and carefully mixed in using a spatula. The slurry was then poured into the foam loop reservoir and the slurry was circulated until steady flow was obtained, to be sure that the whole circuit was filled with base slurry. For test 1the cement pump rate was set to approximately 4 l/min. The foam generator tee was assembled with a 0.15 mm choke and set up with 60 bar pressure as a starting point. When the circuit obtained steady flow, the nitrogen supply valve was opened. The reservoir level was increasing and the nitrogen supply shut off after totally 20 seconds. The pump was also shut off and the reservoir was disconnected. The foamed slurry was poured into a beaker for stability measurement. Two samples were also taken for bubble size studies. The cement pump rate, choke size and nitrogen pressure was changed during testing as seen in table 3 in chapter 5.1.

The testing showed that the planned level indicator in the reservoir was hard to read and the solution considered not applicable.

5. Results

5.1. Foam cement results

Generally:

The first observation from the foam generator loop was that the base slurry containing foamer seemed to create big surface bubbles immediately after the steady flow was obtained. As the nitrogen supply was opened, the second observation was that the flow from the return hose was pulsating. This gave turbulence in the reservoir and more large bubbles were observed.

Test 1:

The density of the foamed slurry was measured to be 0.52 SG, which is under half of the density of the blender foam slurry. By sight, the bubbles was widely distributed and some of them way too large.

Figure 18: Bubbles at surface right after foaming, test 1.

Test 2:

The second test was done with the same recipe, same flow rate and same choke size, but with a smaller nitrogen pressure, 30 Bar. The slurry reached 0.82 SG, after 10 seconds with nitrogen supply.

Test 3:

At the third attempt the flow rate was set to 3 l/min, the nitrogen pressure to 20 Bar and the choke 0.12 mm size. To check if the friction in the loop itself could be a contributor to the low densities seen on test 1 and 2, the density was checked after steady flow was reached in the loop. The density showed 1.44 SG before the nitrogen was injected. Then the nitrogen was added for approximately 4 seconds and the density reached 1.33 SG. It was also observed that the density varied from where the sample was taken in the reservoir. The stability of the foamed slurry was measured after 2 hours static time and showed 1.44 SG at top and 1.52 at the bottom. The sink was measured to be 2 mm.

Test	Rate[l/min]	Choke size [mm]	Nitrogen pressure [Bar]	Nitrogen supply time [sec]	Foam density [SG]	Stability Top/btm [SG]	Sink [mm]
1	4	0.15	60	20	0.52	*	2
2	4	0.15	30	10	0.82	*	*
3	3	0.12	20	4	1.33	1.44/1.52	2

Table 3: Results from the foam generator foaming. Cells marked with * was not measured due to too low densities.

Bubble size distribution:

To be able to compare the bubbles that were created both in the blender and in the foam loop, one sample from each of them were taken. Since only test 3 and the blender test had the same SG immediately after foaming, only these two are compared. Note that the scale on figure 19 and 20 in not identical.

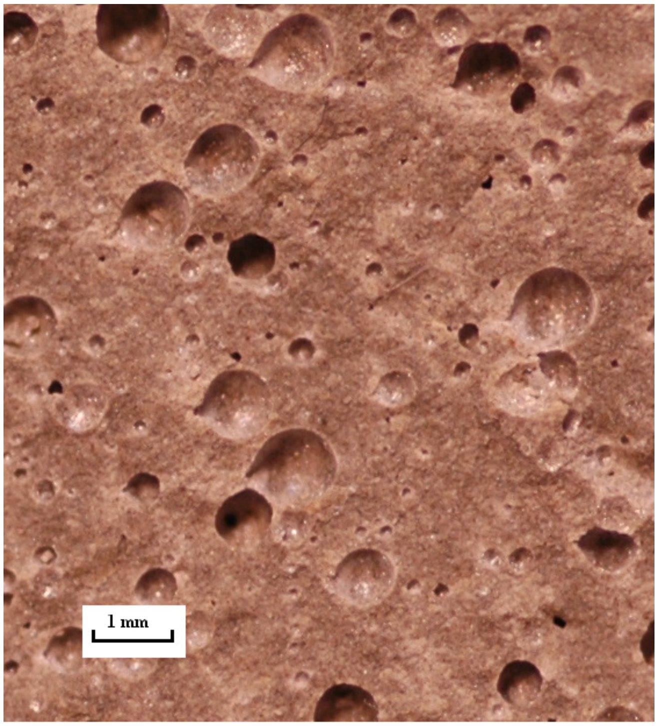

Figure 19: Bubbles Sizes of the Slurry Foamed in the Foam Loop.

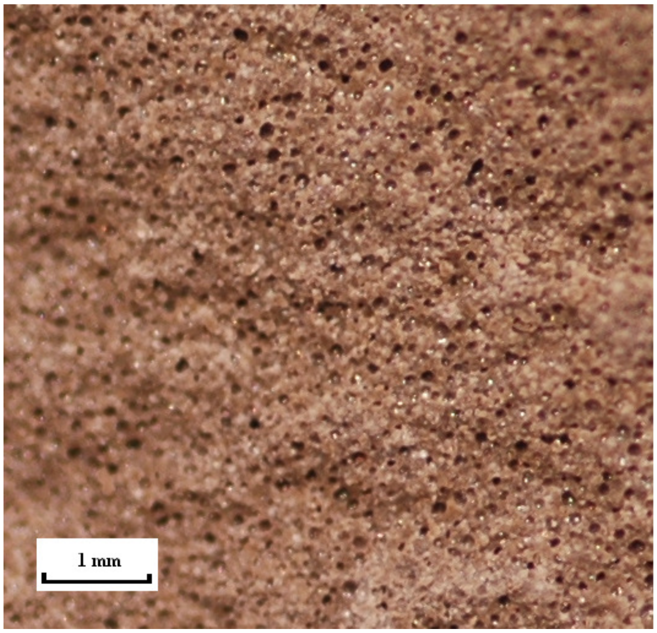

Figure 20: Foam generated in foam blender

As it can be seen in figure 19 and 20, the bubble size of the foam that is created in the foam generator loop has way larger bubbles than the bubbles from the foam blender. By sight, the bubble size distribution in figure 19 is much wider than in figure 20.

Operating performance:

The loop itself was quite difficult to clean. A lot of water was flushed trough it, but the return water was still not clean, as seen in figure 21. The loop was then dismantled and all the components cleaned separately. The pump had many hidden cavities with difficult access, which meant that it had to be dismantled to be cleaned. The pump is made of steal and rubber, and it seemed that the combination of cement and foamer made the friction in the pump movement quite high. After cleaning one could hear unpleasant sound from it, which indicates increased friction from lack of lubrication.

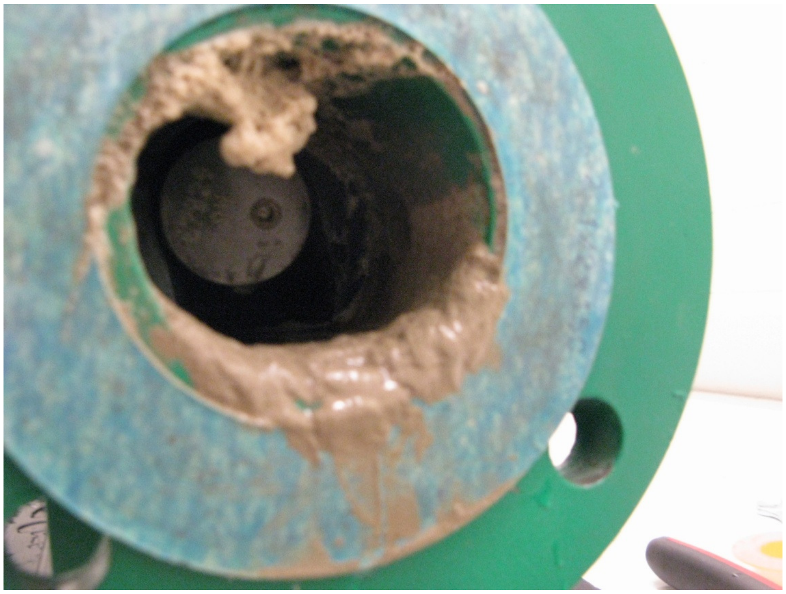

Figure 21: Outlet of pump after repeated water flushing.

5.2. Investigation

Due to that the foam generator loop was able to foam down to 1.44 SG without injecting gas, it was decided to run an investigation test to try to identify why this could happen. The idea was to pump a clear, viscous fluid to better understand what happened. A WG 37 solution was prepared in a 2.5g/l concentration to get the right viscosity. WG 37 is a gelling agent used by Halliburton.

The fluid was poured into the foam loop reservoir and the pump started smoothly. In the beginning there was a lot of air coming out of the return hose. The air that came out in the beginning is probably the air that is trapped in the system before the flow is started.

After approximately 15 seconds steady flow was obtained at 3 l/min. At this stage it was observed a stream of small bubbles in the return flow that did not stop. The whole loop was checked for leaks with a negative result.

When steady flow was obtained, the nitrogen supply was opened with 0.12 mm choke and approximately 10 Bar pressure. It was observed that the return contained large bubbles and that the gas flow was dominating the total flow. The fluid flow rate was then increased up to 5 l/min and the bubbles decreased in size, but the increased flow rate led to very rapid unwanted foaming.

6. Discussion

The foam cement generator showed that it could create foam. On the other hand, it showed weaknesses in the early bubble development that was observed before the nitrogen was injected. The reason for this could be the friction that occurs when the base slurry is circulated in the loop. This friction can cause turbulence and foam the slurry even before the nitrogen is injected. The investigation test that was performed showed also that there might be hidden air traps in the loop that can lead to unwanted foaming. These air traps may be eliminated with a peristaltic pump, which could have identified more accurately if there were hidden air traps in the pump itself. In order to reduce the friction pressure in the loop, larger ID of hoses could be a solution.

In the third test, the stability test showed higher density and unstable results. This result does not show homogeneous density. An agitator placed in the middle of the reservoir, mixing at low speed, could be a solution to make the foamed slurry more homogeneous.

Another issue is the large bubbles that occur, particularly on the reservoir surface. This phenomenon could be a result of a higher pressure inside the loop than at the outside that make the bubbles expand. Figure 19 and 20 is also confirming that the bubbles from the foam cement generator loop are larger than the bubbles created from the standard multiblade blender. The testing showed that by decreasing the flow rate, the foam did not develop that fast, and the foaming process was able to be slightly controlled. A smaller choke and lower nitrogen pressure could improve the foaming process and give smaller bubbles.

This foam cement generator loop could have been assembled in many ways. In order to make it as simple as possible, there are no measuring units such as flow meter or sophisticated pressure gauges. The flow rate is measured manually and the pressure is read manually from the analogue pressure regulator on the nitrogen bottle. The manual pressure regulator was also observed to be varying when the pressure was decreased down to 10 bars. If more sophisticated measurement and regulator equipment had been used, the cement flow rate could have been used to slave the nitrogen injection rate to the desired level and given the right gas-cement ratio.

Another challenge of the loop construction is that the level reading in the reservoir is quite hard. When the foam loop is running, and the level is rising, the big bubbles at the surface are relatively messy and precise readings were somewhat difficult. An accurate densitometer could be a solution of this challenge, but would make the complexity even larger. The reservoir tank could also have been formed in another way which could have made the level reading easier and more reliable.

Finally, all the suggested options in this part could be done to improve this foam generator loop. A closed, pressurized loop with controlled nitrogen injection rate that is slaved by the cement flow rate is, from my point of view, the option that would give the best improvement. A closed, pressurized loop would also contribute to decrease the bubble expansion.

7. Conclusion

The foam cement loop is able to create foam using the principle of injecting nitrogen by the tee shaped injection joint.

The challenge is to be able to control the foam quality and limit the size of the created bubbles.

As possible improvements, a pressurized closed loop could be a solution to minimize the bubble expansion. Controlled injection of nitrogen that is slaved by the cement flow rate could also contribute to a more controlled process of obtaining the wanted density.

8. Nomenclature

- BHCT-Bottom Hole Circulating Temperature
- Bc-Bearden unit
- BWOC-By Weight of Cement
- BVOW-By Volume of Water
- FYSA-Fann Yield Stress Adapter
- BSD-Bubble Size Distribution

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