Experimental results of pipeline dewatering through surfactant injection

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Abstract: Liquid loading is a common problem affecting hydrocarbon production both in well and pipeline. Pipelines transporting hydrocarbons from the wells to the downstream facilities often come across a hilly terrain, which could be considered the main reason of liquid loading phenomenon. Currently the main technique used to solve the problem is the mechanical pigging. Nevertheless, this technique is not free of risks, in fact when the mechanical pigging is possible, operators and engineers have to deal with several issues. This paper presents an alternative method to deliquify pipelines, by using foamer injection. Even if in its preliminary stage, this research work represents a breakthrough since the feasibility of the method can allow an easier, safer and cheaper solution of the water accumulation in pipelines.

The effectiveness of pipeline deliquification treatments by foaming injection is difficult to predict a priori, due to a high number of variables affecting the foam formation and transport within the pipeline. In this paper the issues related to the application of this method are described and some preliminary results on foam formation conditions, obtained on an experimental test bench are presented.

Keywords: pipeline deliquification, liquid loading, foam, foamer, surfactant.

1. Introduction

Foam is composed of a continuous liquid phase that surrounds and traps a gaseous phase and can be treated as a homogeneous fluid with both variable density and viscosity (Lord, 1979).

Since foams always contain more than a minimal amount of gas-solution interface, they are thermodynamically unstable systems. The surface free energy represented by the interface can be estimated from the knowledge of the surface tension and the interfacial area of the foam; this parameter decreases wherever a foam membrane breaks and the liquid coalesces. Thus, the decomposition of foam into its constituent phase is a spontaneous phenomenon. The solution phase is always denser than the gaseous phase, therefore there is a strong tendency for the former to separate or drain from the main body of foam unless it is circulated or stirred in some way. This drainage leads to instability of variation in physical properties with height and time, which precedes breaking. The surfactant, which plays an important role in stabilizing the films, entrapping the gas bubbles and allowing the foam structure to be persistent, is also included in the liquid phase. The main characteristics of foams are a relatively low density and a high viscosity.

The liquid loading can be easily described as the liquid accumulation in a wellbore or within a pipeline, reducing or clogging up the hydrocarbons flow. This phenomenon affects especially old gas wells, reducing the production and in the worst case, if no action is taken, up to the death of the well. For this reason, the liquid loading has been widely treated in literature. When liquid starts to accumulate in the wellbore, the liquid loading problem arises: this occurs when the gas velocity has not the ability to carry out the produced water. Turner et al. (Turner, et al., 1969) described this phenomenon first with a model called "droplet model", predicting the liquid loading by the movement of droplets along a vertical conduit. Turner discovered a simple correlation based on the gas velocity, defining the minimum gas velocity required for the droplets for not falling back in the conduit. Later, also others models were developed trying to describe the liquid loading with more accuracy, for instance the Coleman's model (Coleman, et al., 1991) which is based on the Turner model, or the "film reversal model" (Taitel & Dukler, 1982).

Liquid loading problems are also present in pipelines transporting hydrocarbons from the wellhead to the downstream facilities. The presence of the liquid into the conduit implies a reduction of the production, but also other aspects have to be taken into account when the liquid loading problem occurs. For example, the continuous presence of liquid into the pipe can lead to safety problems. In fact, the high water content present within the liquid can originate rust and weaken the structure, if this remains in the pipe for long periods. Nowadays the pigging technique is a consolidate practice (Schaefer, 1991) to remove the liquid trapped into the pipelines. This maintenance practice is repeated each time the amount of liquid into the pipelines induces an excessive reduction in the production rate.

This practice involves the use of a "pig", a capsule shaped device acting like a piston, which removes liquid and solid deposits by running along the pipeline. Such operation is not free of risks, rather it opens very easily the way to several problems. The focus of this research is to address the issue of studying and developing an innovative technique, based on foamer injection, to remove liquid from pipelines, in order to ensure production rate and allowing a continuous and safer maintenance of the conduit.

The key idea is based on the injection of surfactant into pipelines, using the foam to remove the trapped liquid; the operation is analogue to that used to unload a gas or oil well, which use is quite diffuse and has been widely treated in literature.

However, there is no evidence of application of this method in real pipelines and, besides the very few studies cited in literature, neither at laboratory scale. A deeper analysis on the conditions required to assure the foam formation in the loaded pipeline is appropriate to increase the possibility of obtaining successful results. In this project the impact of some factors on the foam formation has been investigated with a dedicated laboratory test campaign.

The potential advantages related to a continuous foamer injection can be several, such as:

- Production increment
- More stable production
- A continuous preservation of a low liquid loading

- Reduction of the risk to have hydrates formation
- Reduction of the pigging runs
- Reduction of the slug catchers size

2 Literature Review

The first experiments on surfactants added to air-water flow have been performed by Saleh and Al-Jamae'y in 1997; they assessed the gas velocity required to perform the dewatering of a vertical pipe but not the liquid flow rate. The effects on a vertical pipe was also investigated by Sawai et al. (2004), which demonstrated that the amount of water in the film decreases due to the surfactant effect. Similar experiments were performed by Duangpraset et al. (2008) and Liu (2014). A different test bench was used by Xia and Chai (2012): they performed measurements in pipes with small inclinations from the horizontal by electronic tomography.

There are very few papers in literature dealing with the use of foams for dewatering horizontal pipelines. Fuller et al. (1997), presented a new approach to solve the problem of pipeline dewatering and introduces a new application of foam technology. It is believed that this was one of the very first successful operations of a remote subsea gaslift system. The technique has proven to be very efficient from both viewpoints of cost and logistics.

Lima and Alves (1995) presented a successful concept of using low cost and low density foam pigs for both liquid removal in wet-gas pipelines, and paraffin removal in oil and multiphase flow pipelines. Experimental work was conducted in a laboratory facility, including a small-scale glass manifolds and a 6-inch steel manifold proved these pigs to be very effective.

Sweeney and Hallett (2011) patented a method for dewatering, pressure testing, hydrotreating, suppressing methane hydrate formation and suppressing solution freezing point in pipeline operations, where the solution used in the operations includes an effective amount of a metal formate salt that is sufficient to reduce substantially all or part of a residual water film from the interior of the pipeline during a dewatering operation. In Appendix, a review of several research works focused on the investigation of foam characteristics carried out by Eren (2004) is reported. Benucci et al. (2015) presented the preliminary results of laboratory tests carried out for foam characterization in horizontal pipelines. The foam is a particular type of gas and liquid emulsion, where gas bubbles are separated from each other by a liquid film. Therefore, the foam transports a certain amount of liquid held in its interior. The low-density mixture, in combination with a low gas slippage due to an increment of the exposed surface, make the foam easily transportable by the natural gas flow, obtaining the pipeline deliquification.

The pigging technique is consolidated and widespread, but it has intrinsic hazards; therefore, preliminary analysis should be carried out to allow the correcting pigging procedure (O'Donoghue, 2002). The analysis of the amount of material that the pig should remove is fundamental to limit the possibilities to have a clogging issue, but the estimations of wax deposit, hydrates, liquid trapped, debris, etc., are affected by a large degree of uncertainty. The cost of a shut down due to a stuck pig can be very high, and because of it there is reluctance by the operators to perform the pigging operation. In addition, geometric constraints or the absence of systems to lunch and receive the pig prevents its use are additional issues to take into consideration. The use of pig in old pipelines may be not recommended, especially when the state of the structures is not completely known, considering that the pig transit submits the structure to a high wave pressure.

An alternative technique based on the use of chemicals eliminates the issues raised by a mechanical device like the “pig”. Such technique consists in the injection of surfactants into a loaded pipeline to exploit the foam properties for dewatering. The mechanisms behind the unloading effects is that the surfactants adsorb at the air-water interface; by increasing their concentration more surfactants are adsorbed at the interface and the surface tension of the air-water interface decrease by a factor of 2-3 (de Gennes et al., 2004). Compared to the pigging, the injection of a chemical into a pipeline can be considered not intrusive and it can be performed while producing at normal rate.

Another remarkable advantage is that with the reduction of liquid-foam surge generated, smaller facilities dedicated to receive the liquid are required. Moreover, with a continuous injection of surfactants, it can be possible to obtain a continuous deliquification of the pipeline, keeping a constant low liquid hold-up.

Neverthless the number of advantages of a deliquification based on chemicals, this method cannot remove solid deposits as does the mechanical pigging technique. for this reason this technique can not entirely replace the mechanical pigging, but it should be intended as an alternative method to apply when the pigging is too risky or impossible, or even better, to use in synergy with the pigging, due to the relative low operation costs. A brief comparison of the foamer injection and the pigging technique is proposed in the Table 1.

	Pig	Foamer
PRO	▪ Removal of solid deposits ▪ Removal almost all the settled liquid	▪ Performed while producing at normal rate ▪ Not-intrusive ▪ Reduced possibility to a large liquid surge
CONS	▪ Possibility of stuck pig ▪ Not suitable for some lines ▪ Induce a large and sudden liquid surge	▪ Cannot remove solid deposits ▪ Need an adequate defomer to prevent any carry over to the process

Table 1. Comparison between pigging and foaming

The deliquification using foamers is a consolidated practice in gas and oil wells, and in literature it is possible to find a wide number of studies concerning the onsite interventions. Foam can be considered as a particular type of gas and liquid emulsion, where gas bubbles are separated from each other in foam by a liquid film. Surface-active agents (surfactants) generally are employed to reduce the surface tension of the liquid to enable more gas-liquid dispersion (Lea, et al., 2008). Therefore, the foam transports a certain amount of liquid held in its bulk. The low-density mixture, in combination with a low gas slippage, make the foam easily transportable by the natural gas flow, obtaining the deliquification effect.

The main difference with application in wells is the geometry of the systems, which affects the foam formation mechanisms. A gas or oil well can be considered as a vertical conduit, while a pipeline can be assumed mainly horizontal, with sections slope up to 20°- 30° with respect to horizontal, with the exception of the riser. In a pipeline, there is not the favourable condition that is present at the bottom well, where the hydrocarbon passes through the liquid phase, generating the foam. In the pipelines, the mixing of the gas and liquid phases depends mainly on the type of the flow regime. The flow varies not just along the pipeline, but also during the production life of the well. The type of regime is one of the many variables conditioning the foam formation among which can be included:

- liquid composition
- liquid hold-up
- pH
- pressure
- temperature
- internal pipe diameter
- pipeline elevation profile
- foamer concentration
- foamer type
- injection method
- injection section
- injection rate

It is easy to understand that a good knowledge of "how and how much" the listed variables affect the foam generation is mandatory to perform successful deliquification operations by foamer injections. Moreover, to increase its effectiveness two others important characteristics of the foam are required:

- the foam stability
- the foam quality

Both these characteristics define which type of foam has more affinity with a given fluid composition. In this preliminary stage of the research work, an experimental approach to determine the affinity and the influence of the listed variables has been adopted.

The stability can be described as the time needed to dissolve the foam; the quality is defined as the percentage of gas in the foam mixture at operating pressure and temperature. High quality foams formed of spherical bubble distribution will break down slower than the low quality polyhedron foams. There are two main causes that can disrupt the foam: thinning of the bubble walls and growth of large bubbles at the expense of smaller ones. Moreover foam stability may be greatly affected by brine or hydrocarbon contamination. When brine influx occurs, it will tend to mix with the foam attacking the ionic character of the surfactant and thus reducing the surface tension. Also the temperature in the operation zone is important as much as the chloride content of the brine. With an increase in temperature, the foam tendency in terms of decay increases (Eren, 2004).

3. Experimental Test

3.1 Test Bench

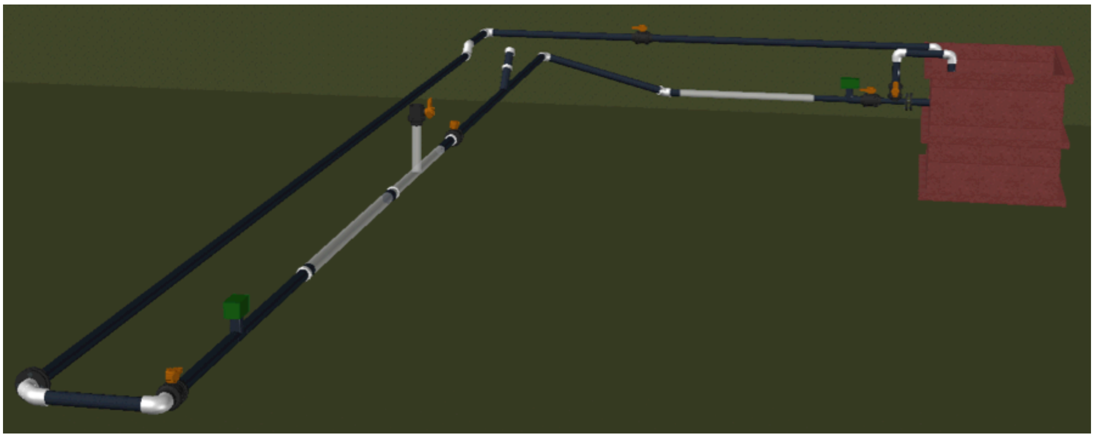


Figure 1: Scheme of experimental test bench

A series of experimental tests have been performed in the MultiLab loop located at the Department of Industrial Engineering and Mathematical Sciences (Università Politecnica delle Marche, Ancona) shown in Figure 1.

In this early stage of the research, one section of the test bench has been modified to study the foam formation conditions within the pipe. A schematic representation of the section of the experimental loop used is reported in Figure 2. The parameters characterizing the tests carried out are summarized in Table 2.

Piping Characteristics and	Operating Conditions
Pipe Internal Diameter (mm)	57
Pipe Material	PVC
Pressure (atm)	1
Temperature (°C)	25
Liquid Phase	Fresh Water
Gas Phase	Air
Riser Inclination wrt Horizontal	45°

Table 2: Experimental tests parameters

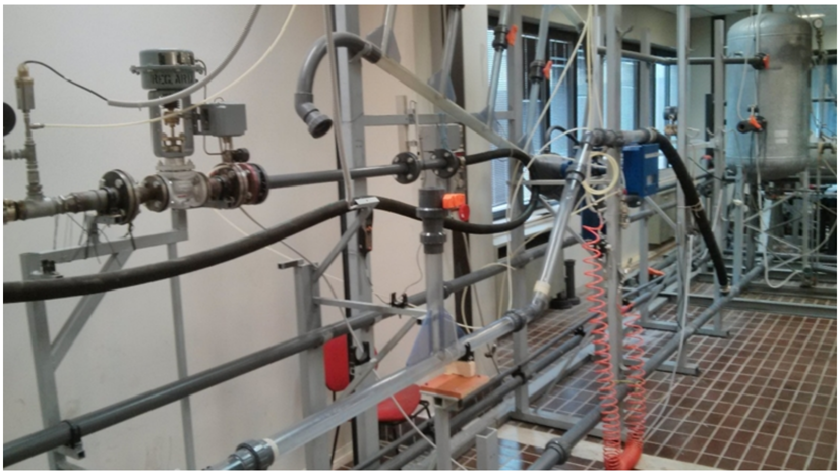


Figure 2: Section of experimental test bench

During the test, the superficial gas velocities necessary for the foam formation onset have been measured at different hold-up: 20%, 50%, 80%. Stability tests have been performed with a hold-up of 50% for 12 hours. Four different chemical foamers have been tested, for a total number of 12 tests for the foam formation and 4 stability tests.

The air velocity has been measured in the air circuit using a helix velocity probe for conduit. To monitor the decay during the stability test, a 12 bit Hi Sense MkII Hamamatsu Camera C8484-05C with 1344 x 1024 pixels CCD camera equipped with a 60 mm Nikon lens, has been used.

Figure 3 shows a representation of the section of the loop used for the dynamic tests, while Figure 4 shows a details of the riser section.

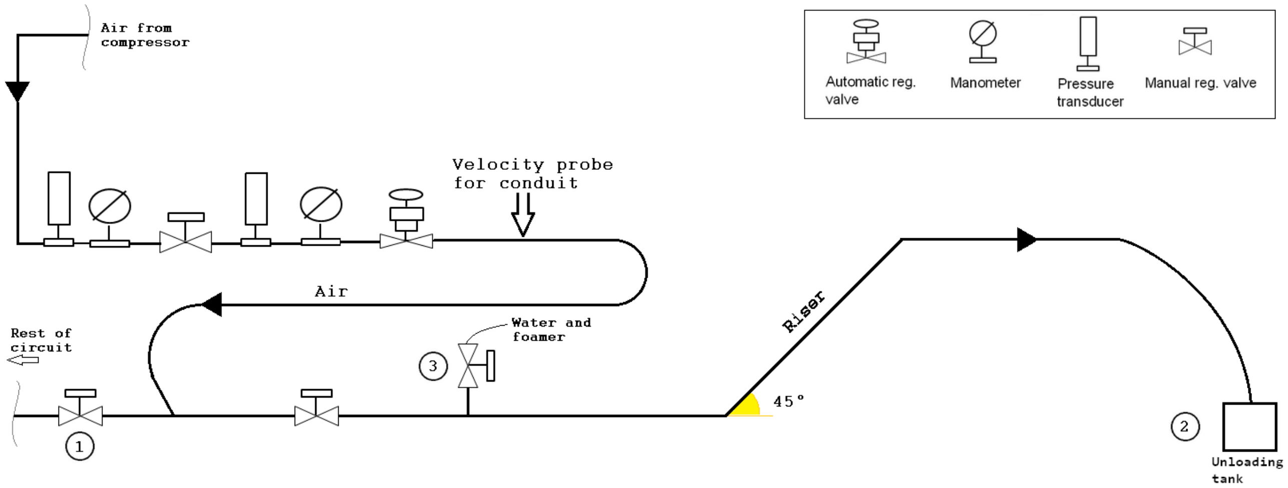


Figure 3: Scheme of the test section.

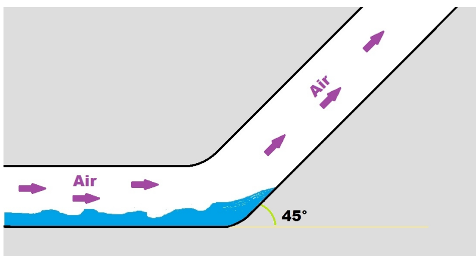


Figure 4: Riser section

3.2 Experimental procedure

To investigate the foam formation relationship linking the air superficial velocity and the liquid hold-up, the following procedure has been implemented: when the system is not working, the horizontal pipe is filled with freshwater until a certain liquid hold-up is reached, then the foamer is poured to obtain the set target concentration. This creates a gradient of foamer concentration in the water along the pipe, but no appreciable differences were noticed pouring into the system a premixed solution of foamer and water. Moreover, in a real application case, the foamer will be injected in a section of the pipeline, creating a gradient of concentration, similar to the first case described.

Once performed the preparatory phase of the pipe, the control valve of the air circuit is opened leaving the air to flow in the pipe through a Y junction. The air velocity is increased following a steps profile, the transitory phase is taken into account maintaining constant the velocity for a fixed time interval. If the foam is not generated, the air velocity is further incremented. This is repeated until the foam formation is achieved. Along this process, the air velocity is recorded by the helix probe and a camera is placed in front of the test section, capturing images with a sampling frequency of 1Hz.

The stability test has been performed following the same steps described above. But in this case, once the foam onset is generated, the gas control valve is maintained opened for a fixed interval time, for each foamer tested. After that this fixed interval of time has elapsed, the air valve is closed and the camera placed in front of the study section starts to sample images with a frequency of 0.017 Hz, analysing the static decay for 12 hours,

4 Results

4.1 Foam formation

The tests in the MultiLab loop have been performed starting from a stratified flow regime. The stratified regime is the worst scenario for the generation of the foam within the pipe, because it is characterized by a lack of mixing between the liquid and gas phases. The liquid has a null velocity, then by increasing the gas velocity, due to the shear stress, the liquid starts to move towards the riser base, slightly increasing, at local level, the liquid hold-up. Continuing to increase the velocity of the gas phase, the flow regime passes from a smooth stratified to a wavy stratified regime. The tests demonstrated the inability of the stratified status to generate foam in both cases. Nevertheless, when the gas superficial velocity reaches a certain value, the system starts to show locally different regimes. In particular, the status passes from wavy stratified to slug in the proximity of the section having the 45° bend, while in the horizontal section upstream the bend, the regime remains wavy stratified for almost the entire length. Figure 5 shows schematically the phenomenon described.

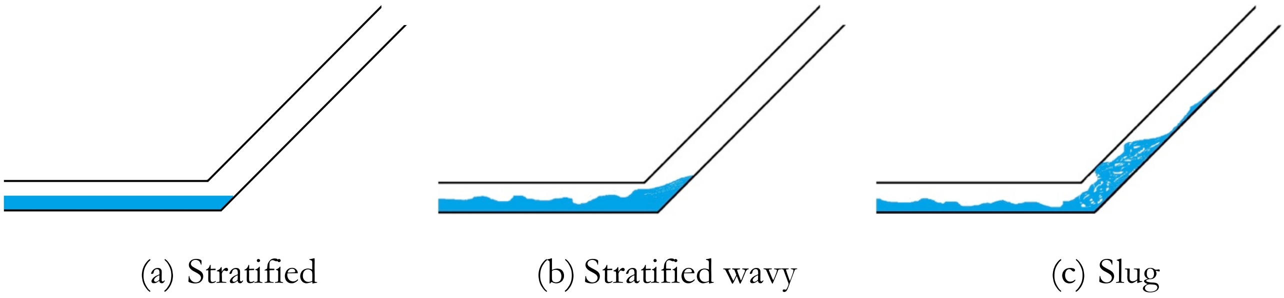


Figure 5: Regime evolution during test increasing gas phase velocity

The local slug regime is characterised by a strong mix of the two phases, having the required conditions for the foam formation. In fact, it was observed that immediately after the slug onset, there is a sudden formation of foam. A portion of the generated foam moves upward the inclined pipe, pushed by the gas phase, as needed to obtain a deliquification of the pipe.

Figure 6 shows the average value of the minimal air superficial velocity needed to obtain the foam formation at different liquid hold-up. Each average value is given by four tests performed for each hold-up, for a total amount of 12 tests. The standard error bars are reported in Figure 6 below the circular marker. The triangular markers represent the minimum air superficial velocities requested to have locally a slug regime for different hold-up without foamer. With a liquid hold up of 20%, it is possible to notice a tendency to have the slug onset at a lower velocity, with respect to the test without foamer. Such behaviour could be attributed to a small amount of bubbles which start to generate during the transition phase from the stratified wavy to slug regime. These bubbles, which hold on pipe wall in proximity of the elbow, reduce the passage section for the air phase, producing a local acceleration of the air flow. This induces a generation of suction force due to the change of pressure, changing slightly the equilibrium transition from stratified wavy to slug regime. It seems, on the other hand, that this effect is negligible at high liquid hold up, where the minimal superficial velocity is almost the same in the case with and without foamer.

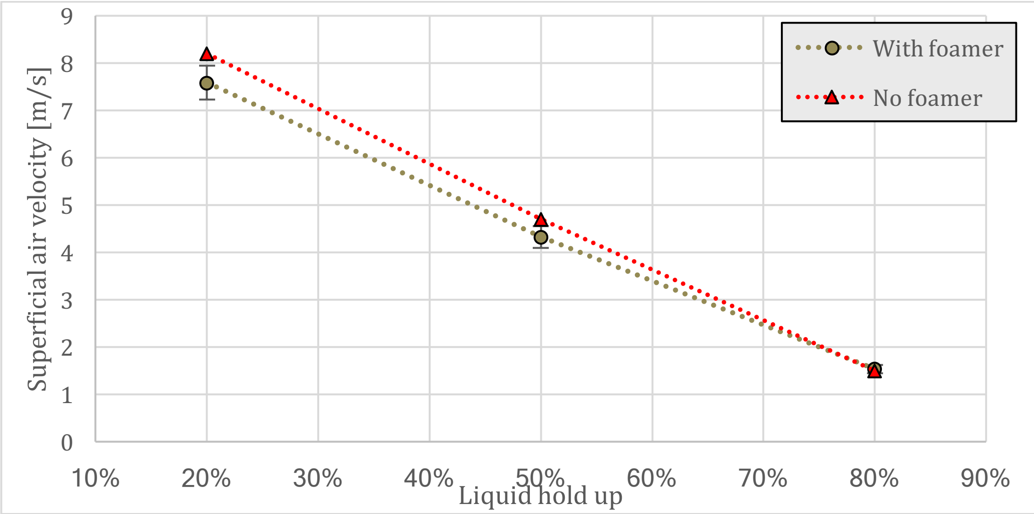
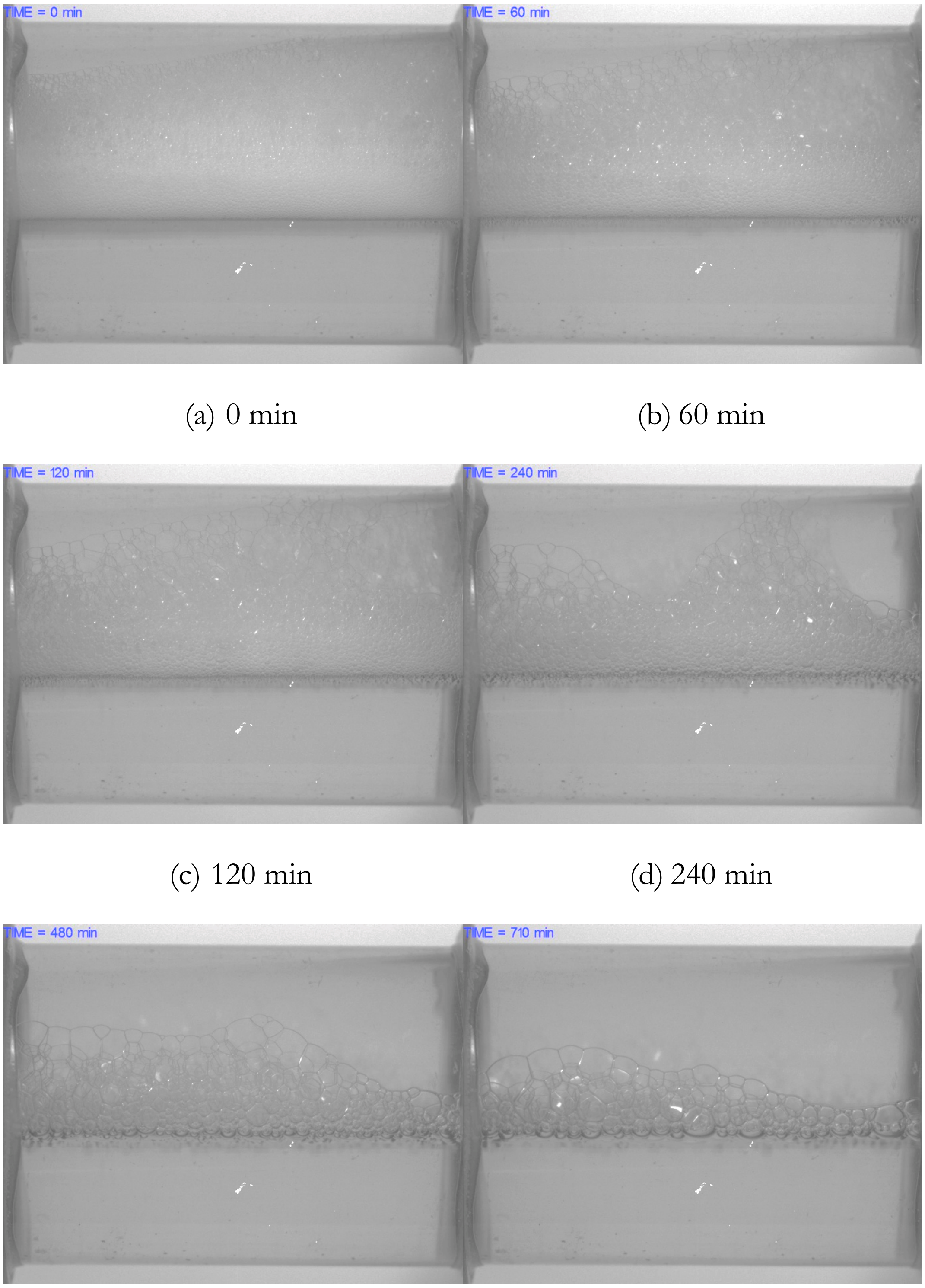


Figure 6: Minimum air superficial velocity needed to have the foam formation within the test bench respect different liquid hold up levels.

4.2 Foam stability

In Figure 7, six frames taken from a stability test performed into the pipeline study section are reported. The tests were performed imposing a 50% of liquid hold-up, using freshwater as liquid. The foamer concentrations were based on the mean values suggested by the producer. Once performed the test, all the images were used to produce a speeded animation, allowing a direct comparison between two products or more; this makes possible the identification of the more suitable surfactant in relation to the trapped liquid composition. The bubbles dimensions of these static decay test are directly dependent on the 'real' formation mechanism, differently from a static test performed in a becker, where the bubbles are generated insufflating gas at the bottom of this latter.



(a) 0 min (b) 60 min

(c) 120 min (d) 240 min

(e) 480 min (f) 710 min

Figure 7: Foam evolution - Frames taken from the camera during a stability test

4.3 Foam analysis by image processing

The analysis of the foam by image processing is a suitable way to characterise the foam behaviour. A high-resolution camera allows the control of the foam decay by analysing the bubbles number and dimension with time. To achieve this purpose several attempts have been performed to correctly identify the bubbles boundaries. The issues arise due to the bubbles overlapping, that makes difficult to identify each single bubble domain. The initial idea was to study the decay in a thin parallelepiped specimen, thus reducing the number of inter-crossing bubbles; moreover, a code able to identify automatically the real bubble boundaries from the 'fake' was developed. The identification is based on two simple criteria:

- real bubbles have their centre of mass within the boundaries. Strange domains, far from a circle domain, may have the centre of mass out of its boundaries. This was set as first check;
- evaluate the eccentricity of the domain. Domains with centre of mass within the boundaries may not be bubble as well. Therefore, a further check on the eccentricity was set to disregard domains having this value far from 1.

Nevertheless, these criteria are not strong enough to assure reliable results, having also the drawback of widely increasing the processing time.

To overcome this issue, another specimen was built, in which the presence of a prism made possible to isolate the bubble from the background. Thanks to the prism properties is possible to see only the boundaries of the bubble that are in contact with the edge of the prism. The image reported in Figure 8 (a) represents the initial condition of the decay analysis for a given surfactant. The foam was created by insufflating air at the bottom of the specimen. Figure 8 (b) shows the end of the decay test. From the image, it is evident that only the layer of bubbles that are in direct contact with the prism are shown. It is easy to notice a significant difference related to the bubble boundaries identification, between the images reported in Figure 8 and those reported in Figure 7. Each image has been divided into different domains to improve the bubbles boundaries identification process, as shown in Figure 8 (c). In the Figure 8 (d,e) a single frame belonging to the identification process is reported. The image (d) is a magnification of the domain entailed between the red and the green line. This has been converted into a binary image; subsequently the algorithm finds each single bubble. The bubbles identified are highlighted in green.

The images were acquired with a sampling frequencies of 0.167 Hz during the decay test. The information acquired are used to better charcterize the foam. For example, as shown in Figure 9 (a), it is possible to assess the foam quality in relation to the percentage of surfactant injected. From this plot it is straithforward to appreciate how the coalescence of the the foam increases over time with the reduction of surfactant concentration. Figure 9 (b) shows a plot where the mean bubble diameter for 4 different surfactants, with the same concetration of 3%, are compared. In Figure 9 (c), it is reported the number of bubble over the decay time for different foamers at the concentration of 3%., considering an initial fix volume. These information are useful for a better selection of the surfactant to use in order to maximize the deliquification effciency.

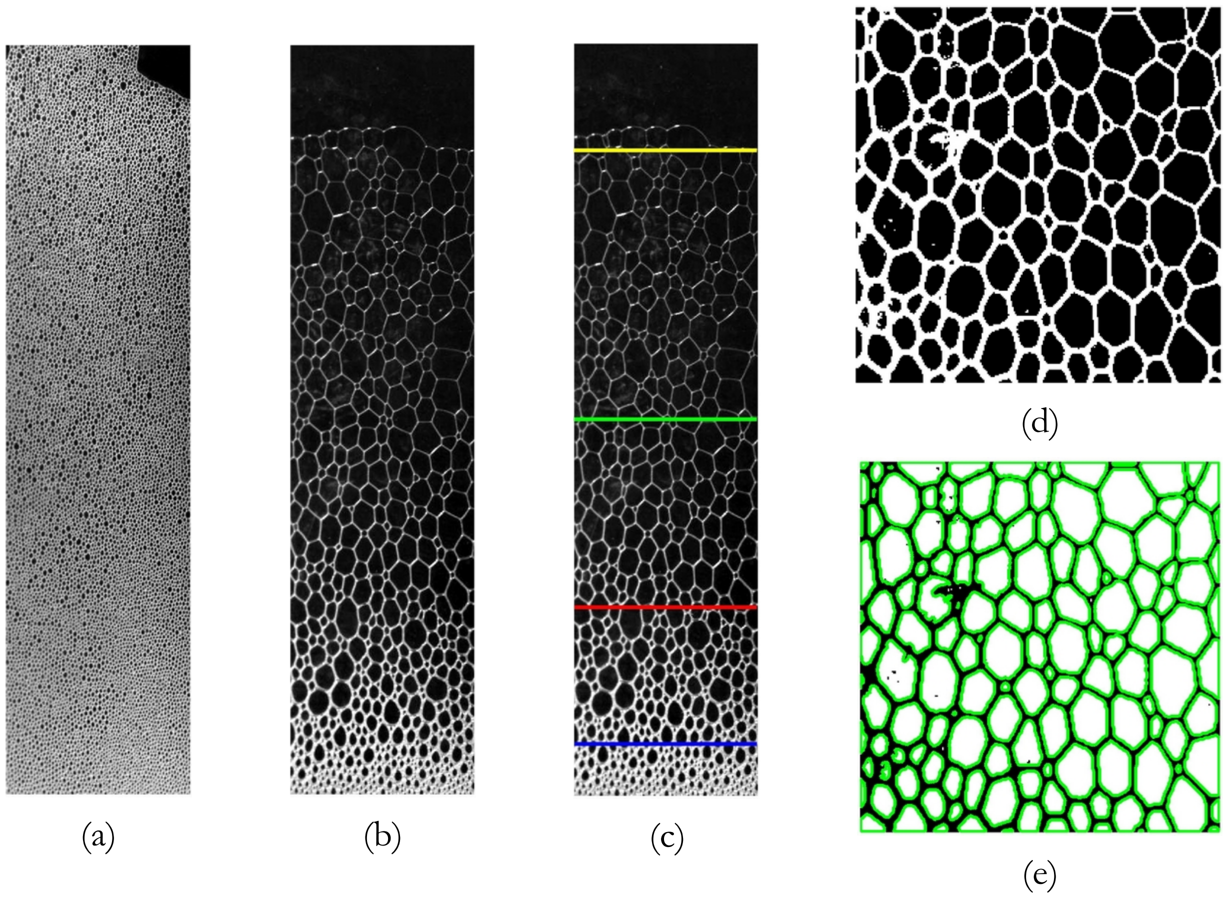
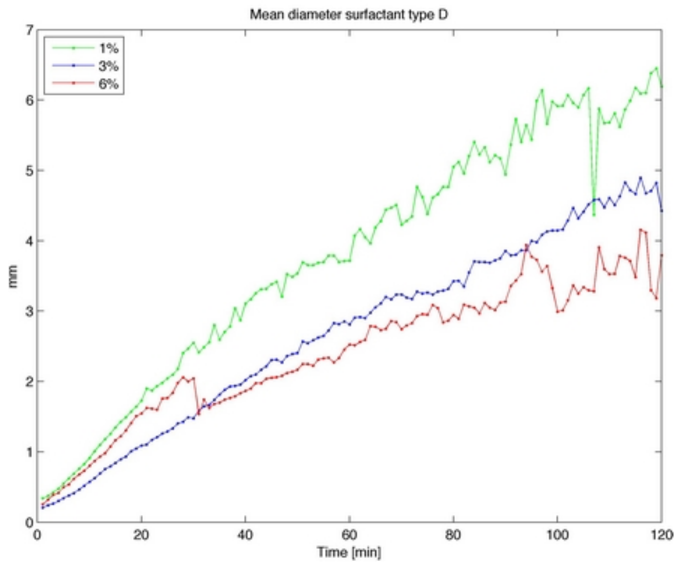
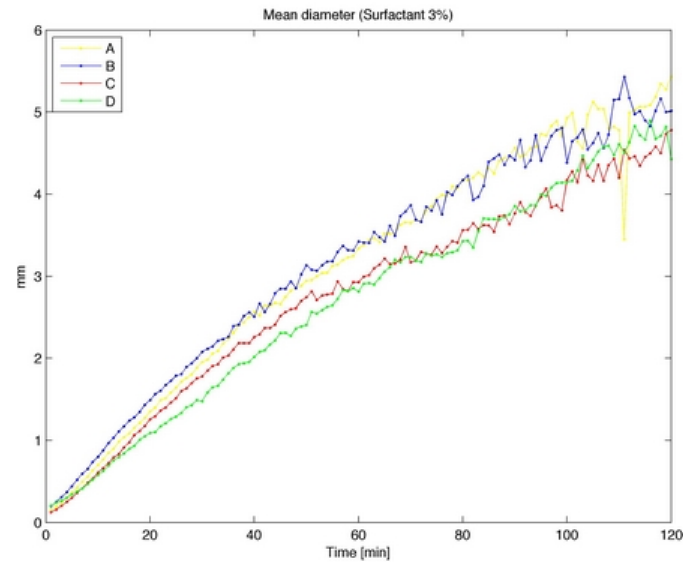


Figure 8: Foam decay test and identification result



(a)



(b)

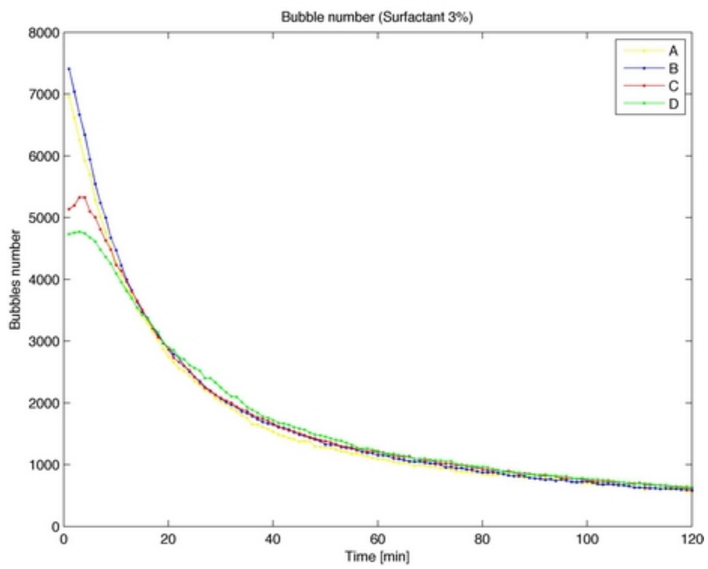


Figure 9: Data extracted from the decay analysis

5 Conclusion

The preliminary tests carried out in this experimental stage of the research show some of the necessary natural conditions needed to generate foam within pipeline to obtain a deliquification. As expected, in our test bench it is not possible to generate foam in the stratified regime; nevertheless, it was observed that the establishment of localized slug regime in a single sections of the system provides the necessary conditions for the foam formation within the pipe, opening the possibility for a system deliquification. The presence of the foamer slightly lower the air velocity is required for the transition of

regime, from stratified wavy to slug, especially at low liquid hold-up. This is attributed to a formation of bubbles during the transition regime from stratified wavy to slug regime.
The test bench used is very small compared to the length of a real pipeline, for such reason our system is not able to simulate some conditions that are established during a real injection of the foamer. The operator injects an amount of foamer based on the total amount of liquid estimated; in terms of percentage it is usually around 3% up to 6% in weight. Therefore, the quantity of foamer injected locally is likely in the order of hundreds of kilograms. The injection of this mass in the system changes deeply the fluid dynamics conditions, 'clogging' the hydraulic section and inducing a localized slug regime requested for the foam formation.
However, the results obtained by stability tests performed into a pipe could be considered more reliable with respect to those obtained by common tests carried out within a becker. In fact, the foam formation mechanism in the pipe is more similar to a real case respect to the injection of a gas through a porous medium to generate the foam. Studying the images, it is possible to perform a preliminary direct comparison between different products, in order to establish which is the more suitable for the liquid. While the application of the image processing algorithm directly on the pipe to analyse the foam decay was challenging. The algorithm provides good result in the analysis of the foam formed inside the becker modified with the prism. These results are very useful to correctly select the most suitable product in combination with the liquid composition.

6 Future developments

The results presented in this paper represent the preliminary stage of the research; starting from this study, the test bench has been continuously developed to analyse a wider set of parameters which could have influence on the deliquification.
In particular, future results will present the analysis of:

- the effect of foamer injection on the foam formation, when the local natural slug regime is not achieved;
- the effect of a continuum injection of water and foamer;

- the effect of the temperature on the system.

Moreover the following tasks are being achieved and results will be presented in a next paper:

- the development of a method to objectively analyse the deliquification power of the foamer, measuring the amount of water that is pulled out form the system;
- equip a test bench section with a prism, allowing the analysis of the foam growth and decay directly on the test bench.

7 Appendix

Authors	
Raza, and Marsden, 1966	They performed a study by generating aqueous foam flowing in both open and closed packed Pyrex tubes. They used four Pyrex tubes of 30 cm long with internal radii ranging from 0.25-to 1.50 mm. They worked with foam viscosity range from 15 cp to 255 poise. They concluded that the foam used in their work behaved like a pseudoplastic fluid. They mentioned that as Γ (quality) increases the foam tends to lessen mass of liquid membranes. They stated that velocity distribution perpendicular to flow direction at low flow rates is parabolic; at higher flow rates it indicated a type of plug-like flow, the degree of which depends on both tube radius, and foam quality. They also gave that apparent viscosity increased with both tube radius and foam quality. They derived an equation describing the streaming potential of Non-Newtonian fluids in circular pipes, where the streaming potential could be defined as the voltage difference between the ends of a capillary tube.
Amiel and Mardsen, 1969	The authors measured the bubble size and bubble size distribution under a microscope, and checked the change of bubble size with time through photomicrographs. They found that bubble size distribution and bubble size (diameter) were dependent on quality. They also found that apparent viscosity was independent of foam quality when corrected for both slippage and foam compressibility. They reported that the foam behaved like pseudoplastic (power-law) fluids with very low gel strengths, which increases slowly with quality.
Beyer et al, 1972	They performed laboratory and pilot-scale experiments aiming incorporation of the results into a mathematical model. They reached to a conclusion that foam quality was principally

	effective in its flow behavior; such as there was tendency in higher viscosity generation and better particle transportation with higher quality levels. The given equations accounted for slippage at the pipe wall and the fluidity component. As given by Beyer et al. the finite difference model made explicit allowance for foam slippage for possible eccentricity of the drill string. The proposed model worked with an accuracy of approximately 10%, with fixed 5-psi pressure steps.
Blauer et al, 1974	They proposed a model in which iteration was not necessary. They arrived at a method predicting friction losses in laminar, transitional, and turbulent flow regimes for flowing foam. They proposed that effective foam viscosity, actual foam density, average velocity and the pipe diameter were functions of Reynold's. They concluded that foam behaved as a single phase Bingham Plastic fluid and that if Reynold's number was used together with friction factor, friction losses for foam could be determined.
Lord, 1979	He developed an equation of state describing the volume of the compressible fluid as a function of pressure and temperature. This relation was extended to the formulation of foam density in terms of pressure, temperature, liquid density, and the gas mass fraction, presuming real gas behavior. He developed a mechanical energy balance for both static and dynamic conditions for the foam circulation in which foam quality, density, and pressure could be calculated at any position within the column of the borehole. Frictional pressure loss was estimated by a mean value of the inlet and outlet friction factor, which was considered as a constant.
Sanghani and Ikoku, 1983	They conducted an experimental study on foam rheology with a concentric annular viscometer that closely simulated actual hole conditions. They reached to a conclusion that flowing foam is a power-law (pseudoplastic) fluid for wall shear rates below 1000 sec-1, and effective viscosity decreased with increasing shear rate. Their study also revealed that most foam drilling operations could be carried out in laminar flow region because of low density and high viscosity of foam, if bottom-hole quality was not less than 55 percent. They developed tables that showed the quality dependence on model parameters. They also stated that, a Bingham plastic model and a yield pseudoplastic model without large errors could represent their data.
Okpobiri and Ikoku,	They presented a model that predicted pressure drop across bit nozzles. The accounted for the compressibility of foam assuming

1986	negligible pressure losses resulting from friction and elevation change. The model they developed for predicting minimum volumetric requirements for foam accounted for frictional losses caused by the solid phase, pressure drop across bit nozzles and particle-settling velocity. Their results indicated that volumetric requirements increased with increasing hole size, depth, and particle size. They presented charts for the determination of flow requirements for various backpressures, penetration rates and pipe specifications.
Reidenbach et al, 1986	An experimental study, backed up with mathematical modeling for the calculation of laminar and turbulent rheology of foams formed of N2 and CO2 was conductes. Laminar flow data were collected in a recirculating flow pipe loop, and the turbulent flow data in a single-pass pipe system. Their study described that laminar flow was a Herschel-Bulkley yield pseudoplastic type as a function of quality, external-phase fluid type and texture. Turbulent flow was described by a modified scale-up relation for the flow of compressible foam. Their work revealed a good correlation with the pressured actual field treatment.
Harris and Reidenbach, 1987	The authors studied rheology of N2 foam under high temperature and pressure, for well stimulation applications. They developed empirical equations to describe N2-foam rheology behavior. Their study revealed that high-quality foams maintain their viscosity better at high temperatures than base-gel fluids at high temperatures.
Harris, 1989	He developed on an empirical approach to determine the effect of bubble-size distributions on the rheological properties of foam. In his study he observed the effect of quality, liquid-phase properties, surfactant type/concentration, gelling agent shear history of foam, pressure on foam rheology. His study revealed that foams were shear-history dependent fluids, which meant the bubble size and dispersion will adjust to an equilibrium state in time at a given shear rate. He mentioned that viscosity was substantially affected by quality and continuous-phase properties and that viscosity was less affected by texture. In his study, higher shear rate, surfactant concentrations and pressure produced finer texture foams. He concluded that continuous phase chemical type was highly effective in foam texture.
Calvert and Nezhati, 1986	The authors studied rheology of liquid-gas foam by conducting experiments on cone and plane rheometers, and also pipe flow. Their study revealed that foam could be modelled by a modified Bingham Plastic system, with a liquid rich slip layer at solid

	surfaces.
Cawiezel and Niles, 1987	They carried out laboratory work with simple Nitrogen foams and gelled foams in order to find the rheological properties of foams by observing quality, pressure, temperature, and shear rate effect. Their work indicated that simple foams exhibit a yield stress, and fit the Herschel-Bulkley model, having a dependence on quality, being a function of foam structure. Their study revealed that apparent viscosity increased with increasing quality and become more pseudoplastic, increasing exponentially. Pressure significantly increased the viscosity of foams more in low-shear rate range, but less in higher shear. With an increase in temperature the apparent viscosity, decreased up to a critical temperature after which little change occurred. They observed no effect on foam rheological properties by exposing them to shear.
Khan et al, 1988	They experimentally studied the steady and time-dependent shear flow properties of high gas fraction liquid foams. In their study they mixed a stream of gas and liquid solution in porous structure in order to have gas volume fractions of up to 98% and observed liquid surface tension, the average bubble diameter, and the gas volume fraction. All of their rheological measurements were done by using a parallel plate mode of a rheometrics Mechanical Spectrometer, at room temperature. The linear viscoelastic properties of foam were studied by using small amplitude oscillatory shear experiments. Their study revealed that steady-shear foam flow behaved like a Bingham Plastic (Shear thinning) with a viscosity being a function of shear rate even at very low shear rates, where as for low-shear rates, they concluded having observed a shear thinning viscosity inversely proportional to shear rate, indicating the yield stress to be the prominent contributor to viscosity, which was increasing function of quality. Their study also revealed that yield stress increased with increasing gas fraction. Oscillatory dynamic experiments revealed that foam behaved like an elastic solid for small deformations. In their study stress- strain behavior of foam was found to be independent of shear rate.
Rankin et al, 1989	They conducted laboratory work on the use of compressible fluid as a circulation fluid. They concluded that less formation damage, less lost circulation, and better hole cleaning would occur by the use of lightened rather than conventional fluids. Their study revealed the pumping rates, for dry air and aerated fluids in order to have a turbulent region to avoid flux momentum in the inclined portion of a borehole. Their study also gave that stable foams provided better hole cleaning than gases, mists or aerated

	muds.
Valko and Economides, 1992	They worked on foamed polymer solutions. They developed constitutive equations, by using large-scale vertical tubes and introducing the specific volume expansion ratio to characterize the gas content of the foam. One of the two advantages of the model proposed is assuming a constant friction factor easing the computation of the frictional losses in isothermal pipe flow. The second advantage is having less number of parameters, which made the estimation of the parameters much easier than other models. In another paper they performed large-scaled experiments to measure downhole rheology of various quality foams of CO2, N2 and mixture of their aqueous phases with polymers. A two-step methodology was suggested, first friction factors were obtained by solving the two-phase flow-equation, and then parameterized rheological models to describe quality dependence of rheology were investigated. They proposed a correlation to represent foam rheology, namely Volume Equalized Power-Law Model. A procedure was also suggested to calculate bottom-hole pressure from known wellhead conditions during fracturing.
Sporker et al, 1991	The rheology of multiphase fluids and constructed a flow loop to allow realistic downhole measurements under field-like conditions was investigated. The interactions between gravitational, frictional and other factors have been investigated.
Winkler et al, 1993	The authors performed large-scale horizontal flow experiments. Applying volume- equalized power- law for polymer foams, they found that model was capable to describe isothermal horizontal compressible non-Newtonian flowing systems independent of pipe geometry. In their experiments increase of the foam temperature had no significant influence on the foam flow behavior, but on viscosity. Foam flow behavior in drag-reducing flowing regimes was also experimented.
Enzendorfer et al, 1994	They used five different small diameter pipes to characterize rheology of foam. The results depicted a relative dependence on the pipe diameter. Apparent slip concept was given to define this dependence. It was proposed that Jastrzebski method after being developed was capable for apparent slip correction rather than classical Mooney' s slip correction. It was shown that the Mooney' s approach to slip correction was not applicable for foams. The specific volume expansion ratio was introduced, it was shown that the flow curves of foams with different qualities and pressures are collapsed into one master curve, which showed

	power-law behavior with no indication of yield stress. It was obvious that viscosity increased with increasing quality. The phenomenon of curves to collapse into one master curve was a testimony of the application of volume-equalized principle giving the dependence of the rheology of foam to its gas and liquid constituents.
Gardiner et al, 1998	They worked on rheological investigation of compressed air foams, and also gave the velocity of foams flowing through horizontal tubes. They utilized Poiseuille-flow rheometers with three different diameter pipes with foam generation by means of compressed air. They showed that a master equation could have been drawn from the experimental data to account for a range of expansion ratios, and pressures encountered for polyhedral-in-structure foams. The data were corrected by the method of Oldroyd- Jastrzebski to account for slip correction that eliminated geometry dependence of foam. Volume equalization method was used resulting in collapse of data points in two different master lines depending on foam texture being either polyhedral or bubbly in its nature.
Kuru et al, 1999	A review study of foam and aerated drilling fluid technology was conducted. They found that there was no general agreement on which rheological model should be adapted. The effect of temperature on the behavior was yet to be investigated, and they also outlined the future needs of the research area.
Saintpere et al, 1999	They used blend of anionic surfactants commercially in use on drilling site in their experiments. They have worked on the formulation in order to enhance the stability of the foam, by changing the surfactant, salt and certain concentrations of water-soluble polymers. Having conducted all of their experiments under ambient conditions, they concluded that paying no attention to transitory regimes or not controlling slip at the wall in steady shear flow measurements would result in a wrong viscosity evaluation. They also concluded that bubble size had a tendency to decrease in size when pumped downhole.
Alvarez et al, 1999	A study correlating the effects of parameters like permeability and surfactant formulation on foam behavior in the two flow regimes (high-quality "dry", and low-quality "wet" regime) and on the transition between the two regimes was performed in this study. Hassler-type coreholder with 4 internal pressure taps was used. They used a video camera to record qualitative bubble texture through the visual cell at the outlet of the core, conducting the experiments at room temperature. Surfactant type

	and concentration, permeability, core layering and flow rates were varied whilst the experiments. They observed higher bubble sized foam in high-quality regime, as contrary smaller bubbles in low-quality regime. They correlated the shift in predominance between flow regimes as permeability; foam formulation and flow rates vary. After this study a guide to select foam formulation and foam quality for field applications in gas injection IOR and foam acid diversion have gained insight.
Rommetveit et al, 1999	An experimental study in a vertical, instrumented test well, to plan an operation in order to better evaluate dynamic pressure and flow effects was carried out. The results of their study predicted gas injection rates fairly good, and the pressure curves of simulated and experimental curves matched well.
Ozbayoglu et al, 2000	A foam flow experiments through 2", 3", and 4" diameter pipes and 8" by 4.5" annular section was conducted. They recorded gas/liquid flow rates, pressures, and temperatures. They investigated the degree of fit by Bingham Plastic, Power Law, and Yield Power Law, to the Generalized Foam Flow Curve. They concluded that wall slip effect may not be neglected and should be considered in establishing the flow curve representing the true flow behavior of foam in pipes. They proposed a foam rheology definition based of foam quality level, e.g. foam was depicted as Power Law model in the range of 70-80% quality, and Bingham Plastic model for 90%. Eventually they mentioned that there was yet no best model for the pressure loss prediction during foam flow in pipes.
Rojas et al, 2001	The stability and rheological behavior of aqueous foams was evaluated. A capillary tube viscometer was used to perform rheological foam flow investigation. Results they have found indicated that the sensitivity of foam to contamination with oil and salts highly depended on the chemistry of the foaming agent system, and crude oil used. The rheological evaluations revealed that flow behavior is highly related on the foam quality for a given pressure, the chemistry of polymer, and the tube diameter.
Sani et al, 2001	They employed an experimental work on xanthan gel and xanthan foam rheology on a pipe flow viscometer at 1000 psi, using a 1/2" pipe. They found that as the foam viscosity increased, there was an increase in foam quality. When the temperature was increased the viscosity was adversely affected.

	They developed correlations between liquid phase properties and foam qualities to predict apparent foam viscosity. They concluded that foam behaved like Herschel-Bulkley model.
Martins et al, 2001	Several experiments to develop a model in order to predict bore hole pressures while drilling underbalanced with foams were performed. The results of their study revealed reliable rheometric data at different foam qualities and derived data to be utilized in designing effective hydraulic cuttings transport design.
Alvarez et al, 1999	They conducted experiments by Hassler-type coreholders with and without internal pressure taps were used. Foam bubbles were observed upstream and downstream of the core with two variable-aperture visual cells, and a video camera recorded the bubble texture at the outlet of the core. They found two different foam-flow regimes as high and low quality. It was understood that a single model could characterize foam behavior. This model correlates the shift in predominance between flow regimes as permeability, foam formulation, and flow rates vary.
Sudhakar and Subhash, 2002	The authors worked on friction pressure loss correlation development for guar based foam fluids through coiled tubing. They run their experiments on foam flow loop investigating the rheology of gelled foams. The loop was capable of characterizing the rheological behavior of foam fluids of different chemical compositions at different qualities under various experimental conditions. Their study revealed that significant pressure drop in coiled tubing is observed as compared to that of a straight pipe. The pressure drop along coiled tubing was determined to be a function of Reynolds number. They proposed the pressure loss correlation to be used for different dimensions of coiled tubing. They also investigated rheological behavior of guar gel and guar foam fluids using a 1⁄2" pipe viscometer at 1000 psi and temperature ranges of 100 to 200oF. In their study they developed a prediction methodology of consistency index and flow behavior index determination of guar foams. They concluded that for the shear rate of investigation foam fluid rheological behavior followed a power law model. They also mentioned that higher quality foams produced higher shear stresses and viscosities, and at high foam qualities the apparent viscosity of foam increased exponentially with foam quality.

Guo et al, 2003	A model coupling frictional and hydrostatic pressure components in vertical and inclined boreholes was developed. The model is accurate enough for planning foam drilling. Gas to liquid ratio is an important factor affecting depth limit and ECD in stable foam drilling.

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