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Analysis of the applicability of foamed fracturing fluids

Part of the studies presented in this report were carried out under ENFLUID – Polish-Norwegian research cooperation project funded by the National Center for Research and Development. The project was implemented by the following listed partners: Silesian University of Technology – promoter, INiG – PIB (Oil and Gas Institute – National Research Institute), University of Stavanger. Data analysis presented below are a continuation of the research presented in the article *Analiza możliwości zastosowania płynów energetyzowanych do szczelinowania*. The increasing demand for oil, has resulted in the interest about issues concerning the stimulation of resource extraction, even those that cannot be extracted using traditional methods. Therefore, the improvement of fracturing methods is today one of the most important tasks in the field of oil mining and national industrial practice, especially in shale formations fracturing. The use of water-based fracturing fluids may lead to so-called formation damage caused by the swelling of clay minerals. In the search for alternative fracturing methods, attention was paid to energized fluids as a promising method of fracturing water-sensitive formations. Therefore, this report presents studies, the aim of which was to verify the potential possibility to use nitrogen-based fluids for fracturing operations.

Key words: fracturing fluids, foams, nitrogen.

Analiza zastosowania płynów do szczelinowania na bazie pian

Coraz większe zapotrzebowanie na ropę naftową powoduje zainteresowanie zagadnieniami stymulacji wydobywania zasobów, także tych nie dających się wydobyć tradycyjnymi metodami. W związku z tym doskonalenie metod szczelinowania jest dziś jednym z najważniejszych zadań w zakresie górnictwa naftowego, również w krajowej praktyce przemysłowej, szczególnie podczas szczelinowania formacji łupkowych. W przypadku, gdy użyte cieczki szczelinujące wykonane są na bazie wody, może wystąpić tzw. uszkodzenie przepuszczalności, spowodowane pęcznieniem minerałów ilastych. W poszukiwaniu alternatywnych metod szczelinowania, zwrócono uwagę na zastosowanie cieczy energetyzowanych, jako obiecującej metody szczelinowania formacji wrażliwych na obecność wody. Dlatego w niniejszym artykule zaprezentowano badania, które miały na celu sprawdzenie potencjalnych możliwości zastosowania płynów na bazie azotu do zabiegów szczelinowania.

Słowa kluczowe: płyny do szczelinowania, piany, azot.

Analysis of the applicability of N₂ and CO₂ for fracturing

Hydraulic fracturing is nowadays the most popular method of stimulation of oil and gas deposits in shale formations. This was the very efficient technique, that made the extraction of hydrocarbons from unconventional deposits feasible. Hydraulic fracturing consists of the controlled creation of fractures in the reservoir and parent rocks of hydrocarbons, by injecting under high pressure, significant volumes of a suitable fluid, into the formation through a well. The resulting

fractures are kept open by introducing proppant into them, e.g. sand, allowing the return of injected fluid (and then recycling of the so-called flow back) and the increased inflow of gas or oil into the well. Fracturing is necessary to enable the exploitation of hydrocarbons deposits from: formations with very low permeability in which tight gas is accumulated, coal and gas-bearing shale beds [9]. The use of water-based fracturing fluids may lead to so-called permeability damage

caused by swelling of clay minerals or effects of other physical and chemical mechanisms occurring in the fractured formation [3]. It turns out that in numerous Polish shale formations clay minerals can be found, which under the influence of traditional fracturing fluid (water-based) swell and narrow natural fractures and microfractures, thus impeding then inflow of gas or oil into the well. Apart from hydraulic fracturing, which is based on the use of water as a base fluid, other fracturing technologies have been developed as well: e.g. waterless fracturing using LPG (e.g. pentane in the form of a gel) and with the use of N_2 or CO_2 .

Energized fluids have been used in numerous areas of the oil industry such as: hydraulic fracturing, EOR, etc. Foam-based fluids containing polymers exhibit, among others, excellent reservoir rock stabilizing properties, especially in contact with shale rock which is destabilized in the presence of water. Foams are a stable mixture of liquid and gas. In order to produce a stable mixture surfactants are used, which concentrate on the gas/liquid interface, and decrease the surface tension at the phase boundary. Properly selected surfactant stabilizes the thin liquid film and prevents gas bubbles from fusing with each other. Fracturing technology using energized fluids has the following advantages:

- can be used in formations containing clay minerals,
- is water-saving,
- increases productivity of the well after fracturing,
- produces higher density and coverage of fractures,
- reduces formation damage,
- faster cleaning of the well after fracturing,
- enables the possibility of simultaneous underground storage – in the case of CO_2 .

Foamed or energized fluids are often obtained through the use of nitrogen or carbon dioxide. The most common technique is the use of water-based energized fluids containing N_2 or CO_2 . Depending on the concentration of gases, we obtain a foam containing more than 65% of gas (in such a case the foam quality is 65% or more) or an energized fluid – containing less gas (up to 52%) [1]. In the case of energized fluids, some literature sources give even lower nitrogen or carbon dioxide concentrations – about 20÷30% [11]. According to classification after Gandossi [6], the following products are in use: mists – 95%, foams – 50÷95%, and energized fluids containing 5÷50% gas. Due to ambiguous determination of the boundary between foam and energized fluids, foamed fluids are usually called foams.

Fracturing using nitrogen involves waterless or water saving fracturing techniques. Nitrogen started being used as a supporting aid in traditional mining operations as early as in the 1960s. However, just as in the case of carbon dioxide, nitrogen use on a larger scale in the USA did not start until two decades later.

Pure nitrogen is used rarely, and most often it is added to energized fluids or foams. Just as in the case of carbon dioxide, it must be transported under pressure and in low temperature. It is heated and expanded on site, and next injected into the well. Fracturing is usually carried out in two stages – first using nitrogen only (60% of the fracturing medium) in order to create a mesh of fractures, and next with the addition of proppant (40%).

The main advantages of nitrogen use include faster cleaning of the well and the low costs of nitrogen acquisition, which is the main component of air. On the other hand the possible disadvantage is the need for high efficiency pump units, and difficulties with transport of the proppant. All this makes this method less popular, and is used only in the case of shallow formations.

The texture of foam produced using CO_2 is similar to the one produced using N_2 , but carrier capacities of carbon dioxide are greater, compared to nitrogen foams. On the other hand, however, foams produced using CO_2 are characterized by higher flow resistance compared to nitrogen-based foams, especially during the stages of pumping with high proppant concentration.

During fracturing, good filtration control is necessary to form proper fracture geometry, and ensure proppant transport into it. At the beginning of the fracturing process, this depends on the permeability of formation. At a further stage, in the case of gelled single phase liquids, it is controlled by the creation of a filter cake on the fracture walls, the permeability of which is lower than the permeability of reservoir rock. The gelled liquid-based foams also create a filter cake on the fracture walls, but with smaller thickness than in the case of single phase liquids, however, despite this, the filtration of the former is usually lower [8]. This is caused by the penetration of gas bubbles into the pores of the rock, which inhibit the escape of liquid from the fracture. Due to these properties, in the case of foams produced based on linear gels, it is possible to reach the permeability of rock matrix around the fracture, amounting to about 95% of the initial value. Also, when using this type of fluid, the damage to the conductivity of proppant filling the fracture, is significantly lower and reaches the values of 80% to 100% of the base permeability. In the case of cross-linked liquids, this damage is high, but still significantly lower, than in non-foamed fluids.

Foamed fluids are very versatile because of their low density and high viscosity. Research done so far indicate that foam viscosity is highly dependent on the foam quality (gas fraction in the total liquid-gas mixture) and foam texture [5].

Table 1 presents the overview of foam types used as fracturing fluids.

Table 1. Types of foams used as fracturing fluids [6, 7]

Fluid type	Main Composition
Water-based foams	Water with or without polymers, foamer + N ₂ Water with crosslinked polymer, foamer + N ₂ or CO ₂
Acid-based foams	Acid and foamer + N ₂
Alcohol-based foams	Methanol/water or methanol and foamer + N ₂ Water/methanol, foamer + CO ₂
CO ₂ -based foams	Liquid CO ₂ + N ₂
Hydrocarbon-based foams	Hydrocarbon, foamer + N ₂

Foamed fluids became popular as fracturing fluids due to a number of properties such as: small reservoir formation damage, better fluid recovery after fracturing due to “fluid energizing” with gas, low filtration (good fluid efficiency), high viscosity, low flow resistance, good carrier properties of the proppant. There are several disadvantages in the technology of fracturing with foamed fluids such as: low hydrostatic pressure, resulting in high surface pressure, especially when fracturing deep formations, as well as difficulties in obtaining high concentrations of proppant, usually higher costs, and sometimes technological and equipment problems. However, recent advances and progress in the development of foam-based fracturing fluids and additives improving the rheological properties, have allowed the use of foamed fluids even at temperatures reaching 300°F (149°C). Another problem in the design and execution of fracturing operations using foams is the complicated process of pumping highly compressible fluid, as well as unpredictable aspects of filtration, transport of proppant and rheological properties of fracturing fluids of this type. Rheological properties of foams are not easy to estimate because of numerous variables that need to be determined. In addition to standard rheological parameters, temperature and

chemical compositions, there are also other variables typical for the foam rheology, including foam quality and texture, viscosity of both phases, interfacial tension. The key parameter when determining foam rheology is its quality. The increase in the foam quality above the critical value was followed by a clear increase in viscosity. The functional dependence of viscosity on quality depends on other parameters, including shear rate and liquid phase

rheology – Figure 1 [10].

It is very important to stay within the stable foam-quality range during treatment.

When foam quality is lower than 50%, no effect of shear velocity on foam quality can be observed; foam exhibits Newtonian fluid behavior. When quality exceeds 55%, viscosity becomes dependent on shear rate.

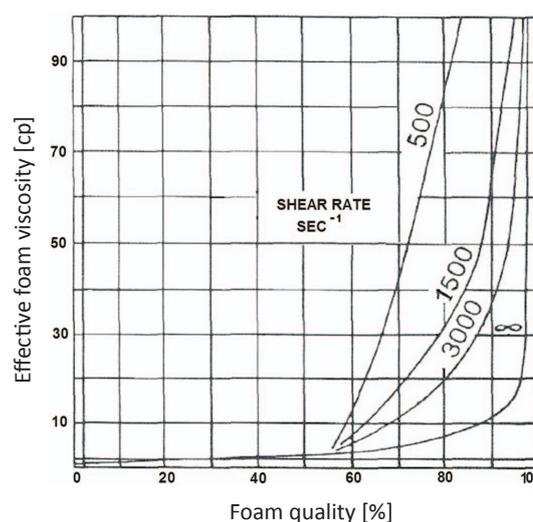


Fig. 1. Foam viscosity vs. quality [10]

Parameters defining foamed fracturing fluids

Energized liquids quality

One of the parameters defining the properties of energized fracturing fluids is quality [4]. Research done so far indicates that foam viscosity depends heavily on the foam quality, i.e. gas fraction in the total liquid-gas mixture. Stable dispersions of gas in the liquid can be prepared for the quality values of less than 52% by e.g. increasing the viscosity of the liquid phase using a polymer additive. A more dense continuous phase makes the joint movement of bubbles and their fusion more difficult. The following substances can be used as stabilizers: guar, hydroxypropyl guar and xanthan gum. Higher foam stability can be achieved by cross-linking the polymer. The liquid phase is then viscous enough to main-

tain the dispersion of gas bubbles, even when foam quality is smaller than 40%. The increase in viscosity of the liquid phase also improves foam rheology and filtration control. Concentrations of proppant in the foamed fluids are generally smaller than those achieved in operations carried out using only aqueous phase.

Half-life of the foam

Another parameter describing the foam is its stability. This is a very important parameter, essential during designing foamed liquid-based fluids. In this case stability refers to the ability of the foam to preserve the resulting foam texture and lack of separation resulting from “bubble breakdown” or

coalescence. Half-life of the foam is the time necessary for half of the liquid used to produce the foam to separate from the foam [12]. Foams with 70÷80% quality were produced using good quality foaming agent, but without the addition of stabilizers such as guar, HPG or xanthan gum, generally 3 to 4 minutes half-lives were achieved [7]. The addition of polymer increases half-life to 20÷30 minutes. Measurements of half-life are performed and used only in the laboratory, for the purposes of qualitative description of foam stability. Foam half-life in the fracture and under high pressure conditions is much longer, than the one measured under atmospheric pressure conditions.

It has been noted that cross-linked polymer-based foams prolong half-life even in the case of poor quality foams (from 30%). The same is true with additives enhancing viscosity, e.g. guar. In this case, addition of natural polymer, leads to stabilization of the system and half-life is extended compared to foams, without the addition of stabilizer [13].

Bubbles size

Gas bubble size distribution and shape is another parameter describing foam quality. Bubble size distribution can be controlled by stirring speed, using the rotor in the foam generator and the stirring time [2]. Bubble size is most often determined in a special chamber that allows stopping the flow of foam and measuring bubbles by means of image analysis.

Foam texture

Another parameter describing the foam is its texture. This is a very important parameter, which is usually not given during the design of foam-based fluids. Foam texture relates to the distribution of gas bubbles and their size. Bubbles diameter in foams for fracturing processes falls within the range of 300÷1200 μm.

Foam texture depends on numerous factors, such as:

- foam quality,
- pressure,

- flow conditions,
- foam generation method,
- chemical composition of the fluid.

This is the type and concentration of an added surfactant that controls the texture and viscosity of the resulting foam. In general the size of gas bubbles is inversely proportional to concentration of a surfactant, which translates into the increase in viscosity. Since foaming requires energy to create new surfaces, surfactants, by lowering the surface tension, enhance the formation of foam and result in its greater stability. The smaller the bubble size, the greater the concentration of surfactants required for foam stability. Figure 2 presents changes in surface tension depending on the surfactant class and applied liquid solvents [7].

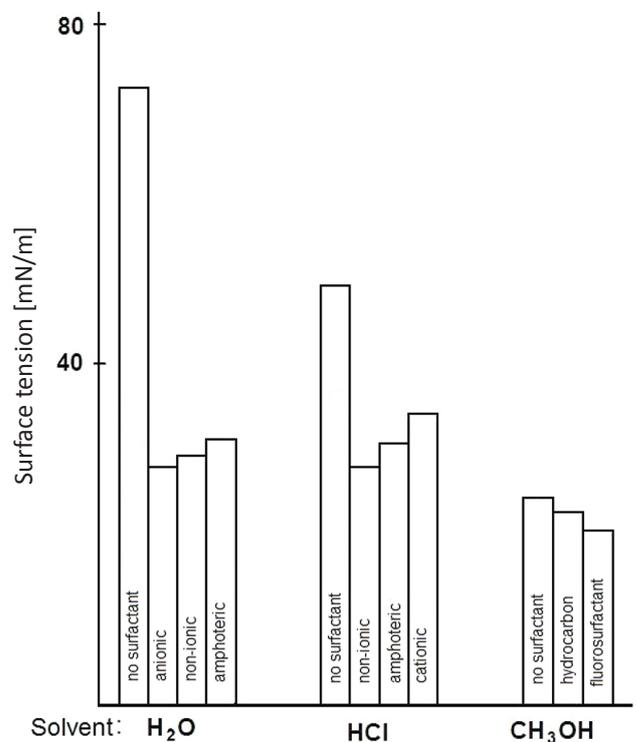


Fig. 2. Surface tensions of various surfactant classes in water, HCl and methanol solutions [7]

Preparation of energized fluids

Composition of technological fluids

Guidelines for the preparation of compositions of technological liquids assume the following issues:

- the use of natural linear polymer-based fluid,
- the use of chemical additives such as:
 - scale inhibitor,
 - clay minerals stabilizer,
 - friction reducer,
 - foaming agent,
 - biocide.

The composition of technological liquid was designed based on acquired knowledge of the physiochemical properties of these liquids on the basis of the following tests:

- fluid compatibility and stability tests,
- surface tension tests,
- capillary suction time (CST) tests of impact of fracturing liquids on clay minerals in shales or other rocks.

For the purposes of preparing technological fluids, a series of tests, including non-foamed liquid compatibility tests were performed. Compatibility observations were conducted

throughout laboratory testing and preparation of test solutions. No incompatibility of the used chemical materials in the form of precipitation of sediments was observed, even after several days.

Surface tension tests proved, that all the tested agents were reducing surface tension compared to the reference liquid (distilled water). The lowest surface tension values were obtained for the additive X at 2 ml/l concentration.

Capillary water absorption tests confirmed, that the most effective and most economical additive, with minimal effect on the tested rock, is the additive Y. This component proved to be effective at as low a concentration as 0.2%, therefore it was used to prepare the fracturing liquid.

On the basis of the aforementioned tests, for further measurements, fracturing fluids with the following composition were prepared:

- 1) fluid no. 1 – water with addition of 0.3% of foaming agent,
- 2) fluid no. 2 – water with addition of 0.8% of foaming agent,
- 3) fluid no. 3 water with:
 - natural polymer,
 - clay minerals inhibitor (agent Y),
 - biocide,
 - microemulsion (agent X),
 - scale inhibitor,
 - foaming agent 0.3%,

- 4) fluid no. 4 water with:
 - natural polymer,
 - clay minerals inhibitor (agent Y),
 - biocide,
 - microemulsion (agent X),
 - scale inhibitor,
 - foaming agent 0.8%.

Method of dosing the individual components of the fluid was determined, and liquid components were being added during continuous stirring in the sequence:

- water,
- biocide,
- polymer – stirring for about 10 minutes before adding next component,
- scale inhibitor,
- clay minerals stabilizer,
- microemulsion,
- foaming agent – adding slowly, without foaming.

Foam testing equipment

For the purpose of energized fracturing fluids' testing, the Foam Loop Rheometer was used (Figure 3).

The Rheometer allows to perform, laboratory measurements of technological fluids in reservoir conditions,

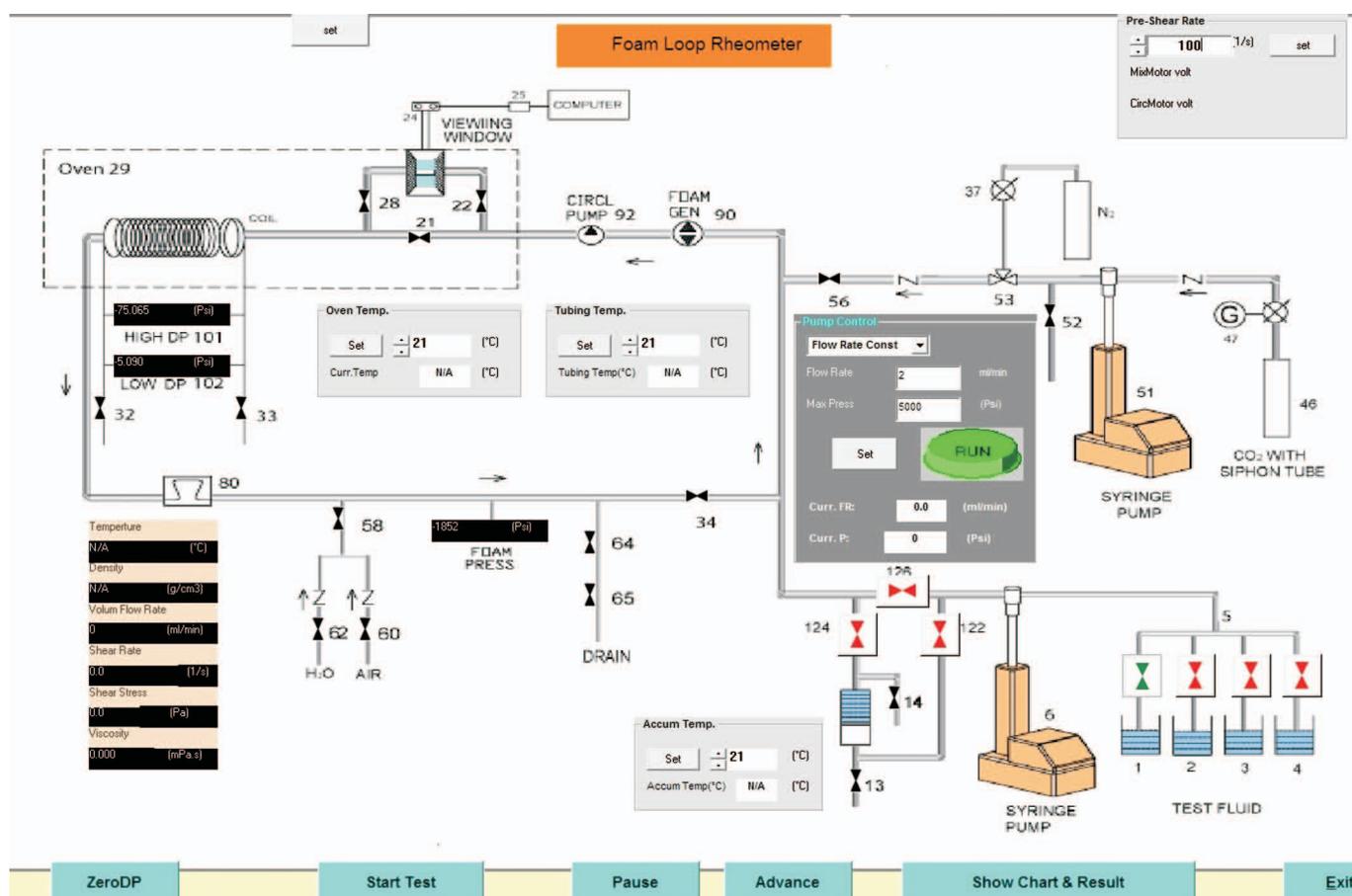


Fig. 3. Experimental set-up schema of The Foam Loop Rheometer for fracturing fluids testing with the addition of N_2/CO_2

measurements of the stability of produced foam with previously specified quality, evaluation of the texture (based on half-life), and rheological properties under the PVT conditions in the well. The system allows to perform temperature measurements up to 120°C and under pressures of up to 5000 psi (34.5 MPa). The device is equipped with two high-pressure pumps for injecting the fluid, controllers for nitrogen and carbon dioxide dosing to the system, a Coriolis mass flow meter for determining flow velocity of the foamed liquid, and for the measurement of its rheology. Comprehensive data, including rheological constants of the Power Law model: n' (power law index) and k' (consistency index) are collected for the control and monitoring of the measurement process.

Tests were carried out at 90°C and 2500 psi. Foamed liquids of the quality between 50% and 70% used for testing contained, in addition to a suitable gas, a polymer, foaming agent – tested in two concentrations, microemulsion, scale inhibitor, clay minerals inhibitor and biocide.

Samples of 500 ml of fluids were prepared. At the beginning, the biocide was dissolved in water. After its complete dissolution the appropriate amount of polymer was added to the mixer, and stirred for about 10 minutes. Next, further

additives were added in appropriate concentrations, depending on the fluid planned to be tested. Liquid prepared in such a way was then placed in the container of the device and sealed tightly. After bleeding the entire tube system, so as no air bubbles were present there, technological liquid was introduced. Next to this stage and making sure, that the entire tube system is filled with water, gas was injected into the system under proper pressure. At the same time, the appropriate operating speed of the engine of the foam generator was set. Initial speed set value was 100 s⁻¹, and then shearing speed was gradually increased to the value of 200 s⁻¹ and 300s⁻¹. If the tests at temperatures higher than the ambient were planned, the proper temperature in the measuring chamber, tank and tubes of rheometer were set. Foam quality was determined based on the density readings from the Coriolis meter. After the desired quality of the energized fluid was obtained, a proper measurements sequence was selected (i.e. circulation rate changes in a given time period) and measurements of rheological properties were performed. Next, the pictures of the obtained energized fluid were taken using a video camera and half-life of the foam was measured.

Measurements of the properties of energized fluids

Rheological properties

Due to numerous possibilities of changing the test parameters, including: the additives used and their concentration, temperature, pressure, foam quality, etc., the test was focused on determining the impact of the concentration of the foaming agent and temperature on the foam stability. Integrated and automated software allowed to make each measurement with a step change of the circulation speed (shear rate) of the foam in the rheometer loops.

During the measurement, the program allows to create charts in real time. An graph of the test temperature, pressure,

shear rate, shear stress, density, viscosity, flow rate, etc. is shown in the Figure 4.

Table 2 and 3 present rheological properties of N₂-based energized fluid. The rheological properties of the obtained foams depend on the concentrations of the foaming agent and the addition of a polymer. Foams obtained using solution with the highest concentration of foaming agent (8 ml/l) were characterized by the best rheological properties. Furthermore, addition of 1.2 g/l of polymer to the tested solution led to a systematic increase in the foam viscosity and stability.

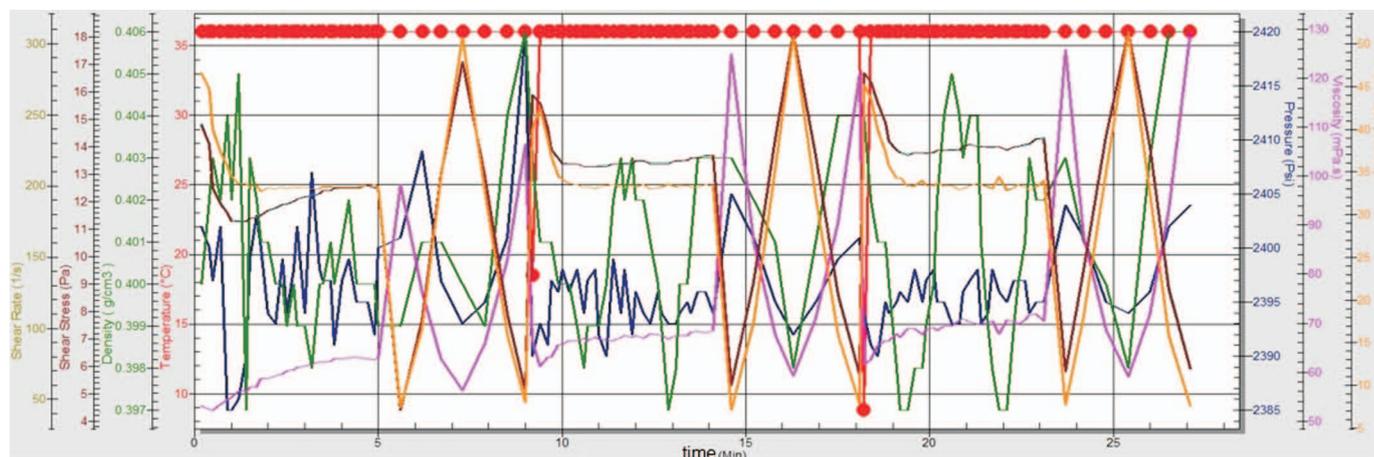


Figure 4. An example graph of the N₂-based foam rheology

Table 2. The rheological properties of the energized fluids 1 and 2 with the addition of N₂ at 21°C and 90°C

No.	Fluid composition	Temp. [°C]	Pressure [psi]	Foam quality [%]	n' [-]	k' [lbf · s ⁿ /ft ²]	Viscosity at a given shear rate [mPa · s]			
							40 s ⁻¹	100 s ⁻¹	170 s ⁻¹	511 s ⁻¹
1.	Fluid no. 1	21	2500	50	0.6052	0.001491	16.6	11.6	9.4	6.1
		90		50	0.3095	0.004855	14.8	9.7	6.7	3.1
		21		70	0.5223	0.002364	19.4	12.5	9.7	5.8
		90		70	0.9389	0.000206	7.9	7.4	7.2	6.7
2.	Fluid no. 2	21	2500	50	0.5028	0.002507	19.2	12.2	9.3	5.4
		90		50	0.4721	0.002133	14.6	9.0	6.8	3.8
		21		70	0.7090	0.002848	46.6	35.7	30.6	22.2
		90		70	0.4729	0.004899	33.6	20.7	15.7	8.8

1 psi = 6.89 kPa; 1 lbf · sⁿ/ft² = 47.9 Pa · sⁿTable 3. The rheological properties of the energized fluids 3 and 4 with the addition of polymer and N₂ at 21°C and 90°C

No.	Fluid composition	Temp. [°C]	Pressure [psi]	Foam quality [%]	n' [-]	k' [lbf · s ⁿ /ft ²]	Viscosity at a given shear rate [mPa · s]			
							40 s ⁻¹	100 s ⁻¹	170 s ⁻¹	511 s ⁻¹
1.	Fluid no. 3	21	2500	50	0.7184	0.002051	34.8	26.9	23.1	17.0
		90		50	0.5425	0.002181	19.3	12.7	10.0	6.0
		21		70	0.7556	0.003877	75.4	60.2	52.9	40.4
		90		70	0.5423	0.005953	52.7	34.6	27.2	16.4
2.	Fluid no. 4	21	2500	50	0.7779	0.001217	28.2	21.0	18.6	14.6
		90		50	0.5154	0.002712	21.7	13.9	10.8	6.3
		21		70	0.6222	0.010693	127.1	89.9	73.5	48.5
		90		70	0.4839	0.015199	108.4	67.6	51.4	29.1

1 psi = 6.89 kPa; 1 lbf · sⁿ/ft² = 47.9 Pa · sⁿ

Half-life

Half-life of the foam was determined after generating the foam of a given quality, after the stabilization stage and performing rheological measurements (Table 4). This parameter was determined using the foam observation chamber (Figure 5). After generating the foam with the desired quality, the flow of the liquid through the rheometer was stopped and the foam was trapped in the observation chamber (static conditions). The longest half-life times were noticed for the liquid 4 and 3 – the foam from the foaming agent at a concentration of 8 ml/l and 3 ml/l in combination with a natural polymer. Foam disintegration time reached almost 20 minutes for the foam of 70% quality at 21°C.

Bubbles size

Gas bubble distribution, as one of the parameters defining the foam quality, was controlled

Table 4. Measurement of foam half-life for the different N₂-based fluids

No.	Fluid no.	Temperature [°C]	Pressure [psi]	Foam quality [%]	Half-life [s]
1.	Fluid no. 1	21	2500	50	38.0
		90		50	10.0
		21		70	41.3
		90		70	12.3
2.	Fluid no. 2	21	2500	50	123.3
		90		50	52.7
		21		70	194.3
		90		70	78.3
3.	Fluid no. 3	21	2500	50	395.0
		90		50	69.0
		21		70	783.3
		90		70	247.5
4.	Fluid no. 4	21	2500	50	429.3
		90		50	161.5
		21		70	1145.5
		90		70	512.5

using a camera for observing the image of the tested foam and for registering photos and videos.

For each picture at least 20 bubbles were randomly selected and then their diameter was measured using a “3 points” method.



Fig. 5. Foam observation chamber

Foam texture

Foam texture was analyzed using images taken with the camera, taking into account the shape and size of the bubbles. Foam texture depends on the type of gas, foam quality, flow conditions, foam generation method and additives used. Energized fluids with a quality of 50% were characterized by even, fine bubbles of a spherical shape, both obtained at 21°C and 90°C respectively. Bubbles produced at a higher temperature were larger than the ones produced at room temperature. Energized fluids with the addition of foaming agent had the most uniform texture, especially those with the addition of 0.8% of foaming agent. The addition of polymer led also to the improvement of the foam texture. Figure 6 (A–D) shows photos of foams with 50% quality. The addition of stabilizers in the form of polymer and a foaming agent clearly shifted the bubble size distribution towards lower values of bubble diameter (photo C and D).

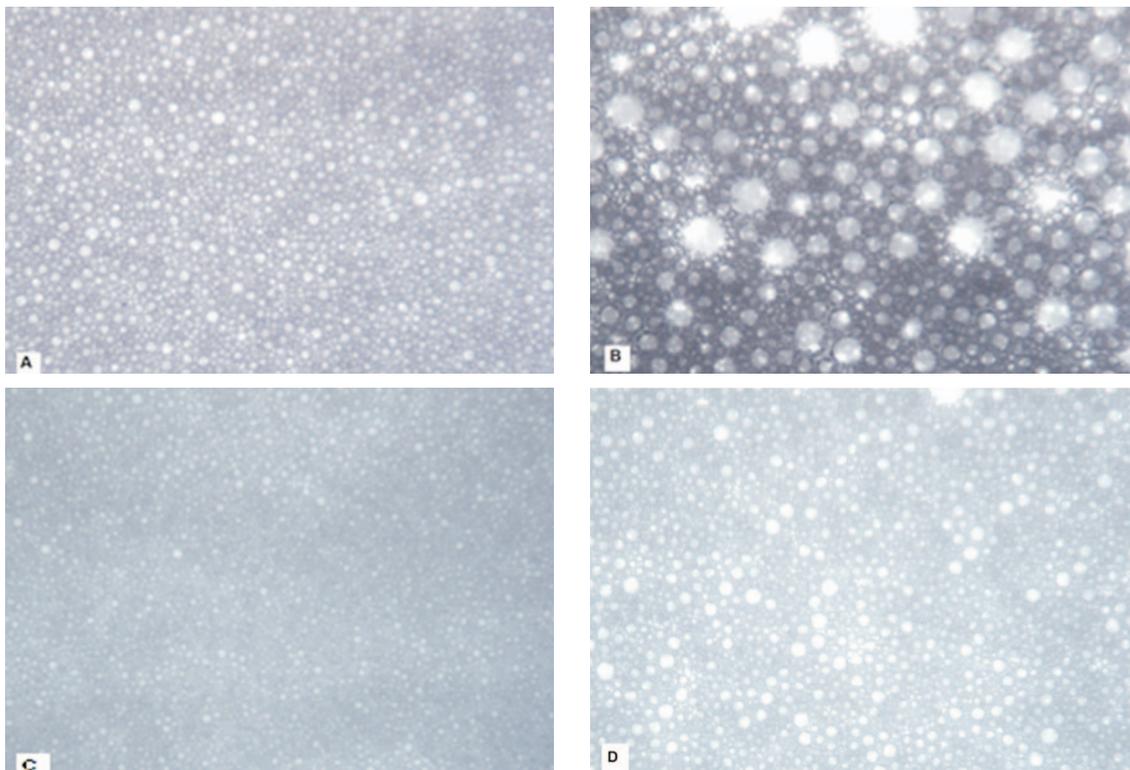


Fig. 6. Photos of nitrogen-based foams (A–D)

A – Fluid no. 1 – 50% quality at the temperature of 21°C; B – Fluid no. 1 – 70% quality at the temperature of 21°C; C – Fluid no 4 – 50% quality at the temperature of 21°C; D – Fluid no. 4 – 70% quality at the temperature of 21°C

Summary and conclusions

Hydraulic fracturing of unconventional deposits, especially those characterized by low formation pressure and water-sensitive ones, is often performed using foams or energized liquids. Compressed gas (nitrogen or carbon dioxide) expands in the foam during the recovery of fracturing fluid, facilitating the removal of liquid from the fracture. The number of

liquid phases is also minimal, since such fluid can contain up to 95% vol. of gas. In the case of water-based fluids, their foaming significantly decreases the amount of liquid that comes into contact with the reservoir formation. Therefore, the foams are also recommended in the case of particularly water-sensitive reservoirs. Thus, their use allows to

significantly reduce the amount of water necessary for fracturing. This considerably reduces also the costs of purchasing water, transport, and adequate preparation, as well as the costs of chemical additives and the costs of storage and subsequent treatment of flowback water.

Our laboratory tests conducted as part of this study allowed to draw the following conclusions.

1. In the case of using N_2 , concentration of foaming agent and the addition of polymer have significant impact on the rheological parameters of the obtained foams.
2. Increasing the concentration of foaming agent to the value of 8 ml/l leads to improvement in the rheological properties thereof, which is reflected also in the extended half-life of the foam.
3. The addition of polymer in the amount of 1.2 g/l increases the foam stability, prolongs its half-life and increases foams viscosity, compared to the viscosity of the fluids of the same composition, but without the addition of polymer.
4. The longest half-life was obtained in the case of foams with foaming agent at a concentration of 8 ml/l in combination with natural polymer. In this case, half-life amounted to almost 20 minutes for the foam with 70% quality, at the temperature of 21°C.
5. Foams with 70% quality have larger bubbles, compared to foams of 50% quality. Despite the foam structure with large bubbles, foams with 70% quality proved to be more stable, and have a longer half-life compared to energized fluids with 50% quality.
6. Bubble size distribution depends on the additives – the foaming agent and polymer, as well as on the temperature. Foams 50% quality were characterized by smaller bubble diameters, whilst foams with 70% quality were characterized by a wider range of bubbles distribution. The addition of stabilizers in the form of polymer and a foaming agent clearly shifted the bubble size distribution towards lower values of bubble diameter.

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