BEER® – Bio Enhanced Energy Recovery – Green Technology for Economic Productivity Enhancement – Part 2

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Abstract

This article aims to introduce a novel environmentally friendly hydraulic stimulation fluid, which follows all the latest regulations and can be accepted by local governments and residents. Lab tests, a field trial, and economic analysis show the performance compared to existing fluid types.

This publication concentrates on the pumpability of the Bio Enhanced Energy Recovery (BEER) fluid and the minimum and maximum boundary conditions in terms of component mass fraction, temperature, and proppant load. The fluid itself is composed of four ingredients: field water, potassium carbonate, a biopolymer, and glass beads as proppants. State-of-the-art laboratory tests to evaluate the recipe composition and the capability of the new fluid regarding viscosity at different temperatures and a pump test were performed.

The blending and pump tests of the BEER fluid have shown that 600 kg/m³ of glass beads can be added to the fracturing fluid without any considerations. The storability of the fluid was tested for 24 h. Viscosity measurements before and after storage indicated hardly any change. Besides, the tested fluid, which was prepared with field water containing bacteria, showed that the novel fluid kills the bacteria by virtue of the high pH – value of the potassium carbonate solution without additional chemicals. Several recipes on polymer combinations and sodium chloride showed potential during the tests and with viscosities, comparable with conventional fracturing fluids.

One of the advantages of using the BEER fluid in comparison to a conventional fluid can be found in a lower required pump capacity, as the density of the BEER fluid is always higher than that of conventional fluids. The BEER fluid can help increasing domestic production not just for natural gas, but also for deep geothermal energy, while reducing the overall carbon footprint under environmentally friendly conditions.

Introduction

In December 2015, the Paris Agreement was signed by 196 parties. It is a legally binding international treaty on climate change, with the goals of limiting global warming to below 2°C, compared to pre-industrial levels and reaching the global peak of greenhouse gas emissions as soon as possible [37]. Carbon dioxide, methane, and nitrous oxide represented 97% of all U.S. greenhouse gas emissions in 2018, which is 6.47 million metric t of carbon dioxide equivalent [38]. Carbon dioxide emissions, which come from various natural and human sources, represent the most significant share. Human-related activities are responsible for the increase that has been seen since the industrial revolution. Human activities alter the carbon cycle by adding more CO_2 to the atmosphere and reducing natural CO_2 storage capacity, like the rain forest [18]. An extensive change in the industrial and transport sector into green energy technology by replacing fossil fuels through renewable energy sources has to be performed, and the related capacities need to be developed to fulfill the Paris Agreement. The share of renewables on a global scale grew in the last decades, but it is misleading to characterize this growth as a significant transition [42]. Significant efforts need to be taken to change from the fossil to the renewable energy age, and this change will take several decades. The "clean" transition fossil energy source natural gas will be required to meet a growth rate of about 2% each year [5].

A significant share will be provided from unconventional shale gas reservoirs. World shale gas resources were estimated in 2018 at 214.5 trillion m³ [39]. Figure 1 shows the world shale gas map presented by the EIA. The shale gas resources are split into basins with and without resource estimations. It can be seen that significant resources are situated in North America, and South America. In northern Europe, several shale basins have been identified, and resource estimates have been carried out. Estimates [3] show that Europe has even more recoverable shale gas than the U.S. The production of shale gas can contribute to a country's energy supply, reduces the dependency on foreign energy suppliers temporarily, creates the home market for the development of exportable fracking technology, and can further improve the current account balance.

The recovery of shale gas requires creating artificial flow paths in the shale layer, done by hydraulic stimulation. After successful fracturing job, artificial lift systems can be used to unload and operate the wellbore. Detailed studies of existing technologies [45-47] and new developments [49-51] have


(Photo: stock.adobe.com)

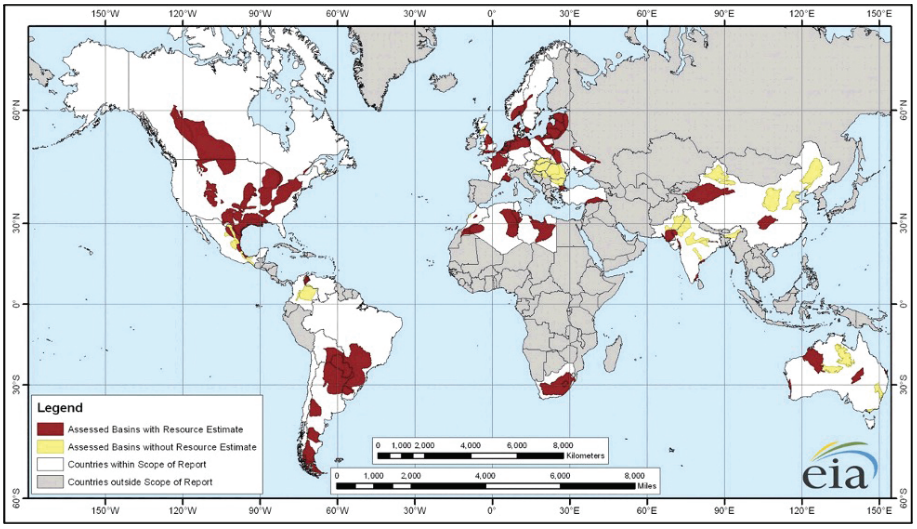

Fig. 1 EIA World Shale Gas Map [39]

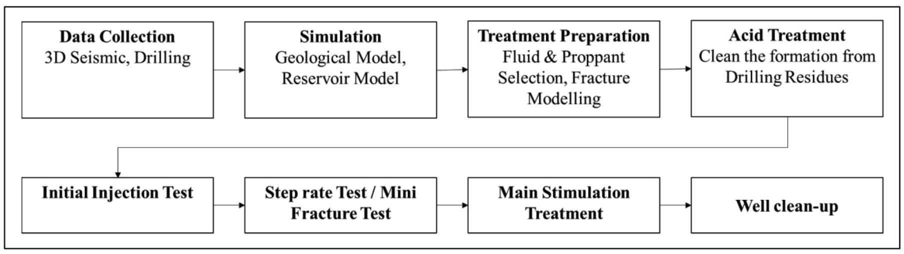

Fig. 2 Hydraulic stimulation process

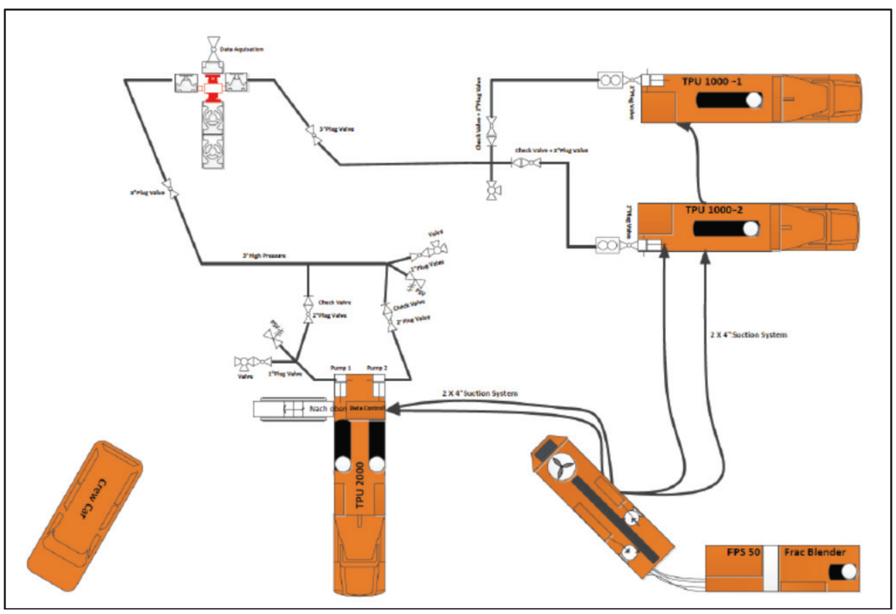

Fig. 3 Hydraulic stimulation process

been performed in the field and in the lab [52, 53].The environmentally friendly cleaning of the produced formation fines has been studied [44]. In the last decade, political restrictions and laws have banned hydraulic stimulation in most European countries due to severe concerns. The U.S. Energy Information Administration [39] and the Alliance [3] have summarized active fracking licenses, fracking bans and license cancellations, and regions with no fracking activities in Europe. Countries like Germany, France, the Netherlands, Scotland, and Bulgaria banned unconventional fracking. The opponents refer above all to possible unexpected ecotoxicological and health risks and seismological events related to the exploration and production of unconventional natural gas reserves [23]. Other factors preventing the fracking boom in Europe include ownership structures, population density (unpopulated land is rare), water availability, and production costs. In the U.S., there are financial rewards for local landowners; in most other countries, private landowners do not own mineral rights on oil and gas in the underground [4].

In 2015, in Germany, 8.5 billion m^3 of natural gas were produced by so-called conventional fracking, mainly in northern Germany from deep sandstone and limestone reservoirs. At the beginning of August 2016, based on proposals by the Federal Ministry of Economics and Technology and the Federal Ministry for Environment, extensive new and more stringent regulations on the use of fracking in Germany were announced in the Federal Law Gazette, ensuring that the protection of drinking water and health has absolute priority [43]. On February 11, 2017, the Federal Water Act (WHG – Wasserhaushaltsgesetz) on fracking came into force. The regulations provide for far-reaching bans and restrictions on the use of fracking technology in Germany. Unconventional fracking projects – which means hydraulic stimulation in shale gas or coal bed methane formations – for commercial reasons are not permitted in Germany until further notice. Nationwide, only four testing measures are permitted, which serve exclusively scientific purposes. The testing measures must be scientifically accompanied by an independent commission of experts. It reports to the German "Bundestag" on the projects that will review the ban on December 31, 2021 [43].

Conventional hydraulic stimulations of sandstones, which have existed in Germany since the 1960s, have also been newly regulated: Fracking is prohibited in water protection areas, medicinal spring protection areas as well as catchment areas of lakes and reservoirs, wells of water withdrawal points for public drinking water supply, national parks, and nature reserves. A permit for conventional fracking projects may only be granted if the mixtures used are classified as not hazardous or slightly hazardous to water. An environmental impact assessment has to be conducted, and the stimulation interactions with neighboring wells need to be evaluated. The well interference or interaction in unconventional reservoirs during the hydraulic-fracturing process depends on the complex interplay of some key factors. These key factors can be grouped into [15]:

– Petrophysical properties (permeability, mineralogy, matrix permeability, natural fractures)
– Geomechanical properties (stress field, tensile strength, Young's modulus, Poisson's ratio)
– Completion parameters (stage length, cluster spacing, pumping rate, fluid and proppant amount)
– Development decisions (well spacing, well scheduling, fracture sequencing)

A trend towards minimal environmental and human health-hazardous hydraulic stimulation fluids to mitigate the risks associated with possible chemical containment failure been observed in the industry in recent years.

Additionally, hydraulic stimulations are not just used to develop shale gas reservoirs, but in enhanced geothermal systems. Enhanced geothermal systems refer to geothermal heat extraction from the ground for electricity generation purposes [29]. Enhanced Geothermal Systems are proposed to extract geothermal energy from high temperature but poor local permeable formations [6]. Hydraulic simulations are used to enhance permeability and to create an extensive network of interconnecting fractures.

This article aims to introduce a novel environmentally friendly hydraulic stimulation fluid, which follows all the latest regulations and can be accepted by local governments and residents. Lab tests, a field trial, and an egological analysis show the performance of the flluid.

Hydraulic stimulation techniques

In contrast to other stimulation processes, which minimize the reservoir damage or reduce production problems, hydraulic stimulations positively affect reservoir productivity [16]. Hydraulic stimulation creates fractures by injecting a specially engineered fluid at a high amount under high pressures and rates and filled by proppants pumped in increasing concentrations [33]. The fractures act like an interface between the wellbore and the reservoir and increase productivity significantly. Outside the created fracture, the reservoir structure remains undisturbed, and the effective permeability of a reservoir remains untouched [13]. The preparation of the treatment is far more complex than the treatment itself. Extensive modeling of the reservoir, fracture propagation prediction, and the fluid using lab tests must be carried out in advance.

Tab. 1 Technical and simple classification system of fracturing fluid types (Patel et al. 2014)

Technical Classification System	
Conventional	Gelling agent + one or more crosslinkers
Water Frac	Gelling agent or viscoelastic surfactant + friction reducer
Hybrid	Gelling agent + acid gelling agent + one or more crosslinkers + friction reducer
Energized	Base fluid + energizer like nitrogen or carbon dioxide to generate foam
Other	Acid frac, gas frac, matrix acidizing

Tab. 2 Table 3: Additive types in German gas wells fracked after 2010 (Bundesverband Erdgas, Erdöl und Geoenergie e.V. 2019)

Additive type	Well Name													
	Bleckmar Z1	Bötersen Z2	Buchhorst T12	Cappeln z3a	Goldenstedt Z10a	Goldenstedt Z17	Goldenstedt Z23	GR Burgwedel 5	Hoehnsmoor Z1	Leer Z4	Soelingen Z7	Völkersen N Z5a-1	Völkersen N Z5a-2	Weissenmoor Z1
Acid							x							
Biocide	x	x	x	x	x	x	x	x		x	x	x	x	x
Breaker	x	x	x	x			x		x	x	x	x	x	x
Encapsuled breaker			x	x	x	x	x	x						
Corrosion inhibitor							x							
Crosslinker	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Crosslinker enhancer	x	x				x			x			x	x	x
Friction reducer		x												
Gelling agent	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Iron control														
Clay control	x	x	x	x	x		x	x	x	x	x	x	x	x
Oxygen scavenger											x			
Proppant	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Scale inhibitor	x	x				x		x	x		x			
Surfactant	x	x	x	x	x	x	x	x	x	x	x	x	x	x
High-temperature scavenger			x	x	x									
Acid buffer			x		x	x	x	x			x			
Foam				x			x							
Fluid loss additive														
pH control	x	x		x	x	x		x	x		x	x	x	x
H_2S scavengerSolvents							x							
Base fluid - water														
Sum of additives incl. proppants														

Fracking Fluid Development

The technical classification system for fracturing fluids distinguishes between conventional, water fracturing, hybrid, energized, and others (Table 1) and results from a continuous development initiated in the 1960s.

Starting in 1947 with gelled crude and kerosene, fracking fluids became greener over time using water as a base fluid. Still, additives like cross-linkers, breakers, surfactants are used. Due to political changes, the trend goes to clean and green biofluids. Every major oil and gas (service) company developed its own "greener" hydraulic stimulation fluid in recent years. The developed stimulation fluids use many various chemicals like cross-linker, buffer, breakers, and surfactants.

The increasing demands and the rising cost of freshwater push products based on produced water [26]. Produced formation water contains a high number of total dissolved solids, causing many fracturing fluids, that were prepared initially for use with clean water, to show significantly lower performance or even completely fail [14]. Zirconium-cross-linked CMHPG fluids have been reported to work with produced water [20], or borate-crosslinked guar fluids were successfully made with produced formation water [11]. Nowadays, slickwater fluid systems consist of 99% of water and 1% of chemical additives, similar to the formerly used additives [2]. Considering that there is enormous variability in various formations with unique properties for fracture treatment and fluid design, it is not surprising that there is no single solution for hydraulic fracturing fluids. The hydraulic stimulation fluids' recipe needs to be customized to meet the specific reservoir and operational conditions.

„Green" fluid options for hydraulic stimulation

Most operators and service companies have recognized that „green" environmentally more friendly hydraulic stimulation developments are necessary to respond to public concerns to continue hydraulic stimulation projects. These companies, universities, and research institutions started to invest in research in alternatives. Research in „green" developments first addresses mainly the concerns of potential drinking water, toxic chemicals, and the amount of water used during the hydraulic stimulation [9]. One solution is to treat flow back water using for example, electrocoagulation technology or to save water by the use of ultra-high-quality foams. An alternative way is a critical assessment of used fracturing fluid additives and the replacement by environmentally „friendlier" products using non-chemical processes, e.g., bacteria control, proppant transport, and proppant flow back control [9]. For instance, Kreipl, M.P., and Kreipl, A.T. [24] developed a hydrogel dissolved without environmentally hazardous chemicals, but allowed for optimized cross-linking without toxic linkers. Research is performed using waste materials, like food waste, grass waste, palm tree waste, among many others, to replace fluid additives [1].

This states the need for the here presented novel environmentally friendly hydraulic stimulation fluid, which does not need further additives and fills the gap of a 100% environmentally friendly fluid system using products accepted in the food industry. The AGES (Agentur für Gesundheit und Ernährungssicherheit GmbH) has also approved the here presented fluid system already.

The recipe of most fracturing fluids contains a list of additives, like clay control, surfactants, friction reducers, biocides, high-temperature stabilizers, etc., to achieve all the necessary fluid properties of fracture treatment. Table 3 shows the additive types used in German gas wells after 2010 until the fracking restrictions arose. The table shows that typically between eight and ten various chemicals have been used. A detailed description of each additive's objectives can be found in the publication of Hurley [17].

Environmentally-friendly hydraulic stimulation fluid

The hydraulic stimulation fluid has to fulfil two tasks during a treatment. First, it has to transfer enough energy from the surface pumps into the formation to create the fracture, and secondly, it has to transport and suspend the proppant within the fractures [8]. The general requirements are the following [30]:

- Adequate viscosity
- Possibility to cross-link the fracking fluid
- Shear-thinning and re-healing tendency (ability to recover the dynamic viscosity after being exposed to high shear)
- Possibility to break the fluid while having no residues (to allow clean-up and to start the production afterwards)
- Compatibility with fluids (formation fluids, HCl)
- Compatibility with proppants
- Low fluid leak-off
- Good transport of proppants
- Low friction properties
- On-the-fly preparation to reduce logistical expenditure
- Environmentally friendly and low cost

To achieve the requested properties, the recipe of most fracking fluids contains additives, like clay control, surfactants, friction reducers, biocides, high-temperature stabilizers. Most additives do not meet the water hazard class 1 as demanded, for instance, in Germany. The novel environmentally-friendly hydraulic stimulation fluid consists of only four components and all follow the requirement of the water hazard class 1, showing long-term stability without any negative impact on the environment.

The environmentally-friendly hydraulic stimulation fluid is a water-based fluid with dissolved salt for increasing fluid density. The salt preferably used is potassium carbonate. Potassium carbonate (K_2CO_3) is a white salt soluble in water, which forms a strongly alkaline solution. Potassium carbonate has turned out as an ideal component of the energy recovery medium. On the one hand, it has a high density and is soluble in water in high amounts, so that the sedimentation inhibiting effect is powerful.

On the other hand, potassium carbonate has strong corrosion inhibiting high-value properties as an energy recovery medium in a deep ground hole. Moreover, it is also well known to act as a shale stabilizer. Beyond this, it is biocompatible (for instance, it can be used in the agricultural industry as a fertilizer). Potassium carbonate is furthermore thermally stable and is therefore employable over a broad temperature range. Moreover, potassium carbonate can also be used for controlling the pH-value of the system. A carbohydrate-based thickener or a biopolymer is mixed into the base fluid to adjust its rheological behaviour. The thickener may denote a powder-like solid produced from many plants such as potatoes, wheat, corn, and wood. The proppant particles are selected from a group consisting of ceramics, bauxite, sand, and glass beads. On the one hand, such proppant particles are biocompatible; on the other hand, available in massive amounts and efficiently maintain open fractures – and therefore the flow path for media – in the formation downhole even in the presence of high pressure. Extensive lab testing on the presented fluid has been performed and has shown the proposed fluid's suitability to be used as hydraulic stimulation fluid. Figure 2 shows the mixed hydraulic stimulation fluid and the glass beads under a scanning electron microscope. Glass beads can be manufactured at extremely high quality, and their overwhelming sphericity can achieve high fracture permeabilities.

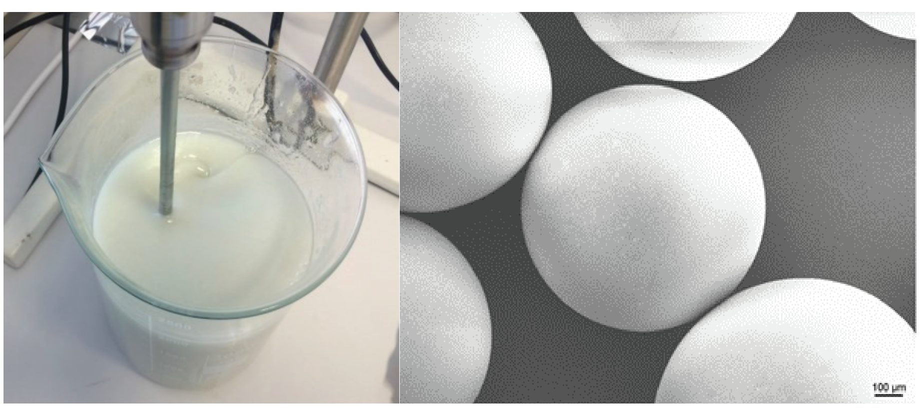

Fig. 2 Fracturing fluid & proppants (left), Glass beads under a scanning electron microscope (right) [28]

Hydraulic fracturing treatment simulation

The hydraulic fracturing treatment simulation was performed to evaluate the fluid and proppant efficiency compared to the software's standard Aqua Mater fluid and the Vistar 20 fluid type. The Baker Hughes Vistar fluid is a zirconate cross-linked system designed so that only very low polymer loading is needed compared to other fluid systems. The base gel is a guar derivative. The selected vertical well to perform this comparison was completed with a 5.5 in. production casing. Based on logging data, the reservoir layer was identified from 3,465 m to 3,478 m. The total number of perforation shots is 20 with a perforation diameter of 0.36 in. Further parameters are summarized in Table 3.

The development of a pumping schedule for the hydraulic fracturing treatment to estimate the efficiency of the novel environmentally-friendly hydraulic stimulation fluid is the primary target. The quality is defined by the obtained fracture geometry parameters and the post-treatment production enhancement evaluation. Modeling the rheological

Tab. 3 Well input parameters

Wellbore Radius	m	0.1
Production Tubing Inner Diameter	in	3.992
Drainage Area	ha	16,2
Aspect Ratio	-	4
Wellhead Pressure	MPa	1,4
Time	days	365

Tab. 4 Simulation input parameters

Laboratory Parameters at 70 °C
Viscosity trend
Power-law fluid exponent trend
Fluid consistency index trend
Fluid density = 1450 kg/m³
Production Tubing Inner Diameter
Estimated Parameters
Fluid cleanup rate =1.0
Fluid efficiency =65 %
Retained permeability = 64 mD
Leak-off properties at 68.95 bar and 82 °C
- spurt volume at 1mD: 0.118 l/m²
- spurt volume at 1000mD: 40.7 l/m²
- wall-building coefficient Cw at 1mD: 0.004 ft/min0.5
- wall-building coefficient Cw @ 1,000mD: 0.10 ft/min0.5
- dynamic leak-off coefficient Cd @ 1,000mD: 1.10-4 ft/min
- filter cake compressibility=0.2

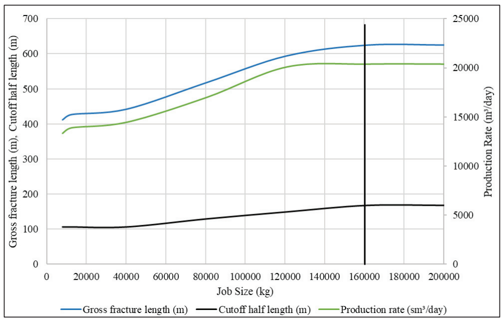

Fig. 3 Sensitivity analysis of the fracture geometry properties and production rate based on job treatment sizes [28]

fluid behavior in the software was the first step. The fluid is a gelled type; it is not cross-

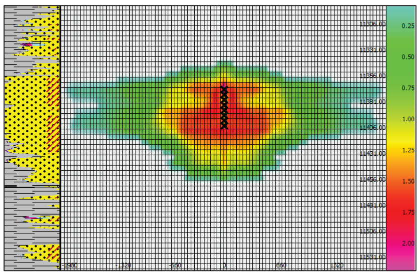

Fig. 4 Proppant concentration distribution at a pump rate of 30 bbl/min (Mukhamedzianova, A., 2017)

linked, as it does not contain any cross-linker in its composition. For fluid modeling, the laboratory rheology results were used, and some of the parameters had to be estimated from the Aqua Master fluid, which was considered the most similar regarding rheology. Table 4 summarizes the simulation input parameters, split into laboratory obtained data and estimated parameters.
The user-defined proppant properties option was used to estimate glass beads performance. A generic correlation is applied to compare user-defined proppant conductivity data with the expected performance of each generic type and size of the proppant. The glass bead density, the mean diameter value, and the conductivity data were inserted, and based on these data, the correlation was performed.

Treatment Design

The treatment selection involves evaluating the sensitivity of the hydraulic fracture growth behavior to identify the optimal pump rate and maximum treatment size.
In the first step, a sensitivity analysis is run to investigate the fracture geometry development for pump rates of 10, 20, 30, 40 bbl/min with the novel fluid including glass beads. The results show that the higher the slurry rate, the wider the fracture and the more considerable the fracture height. The fracture conductivity increases with the slurry rate. By analyzing the proppant concentration for different slurry rates, it is concluded that the proppant is not effectively displaced at 10 bbl/min, resulting in more uneven distribution and a higher concentration of the proppant at the perforation area. As the pumping rate increases, the distribution of proppants improves. As for the fracture geometry parameters, it can be concluded that there is not as much difference for the geometry parameters between the cases with 30 bbl/min and 40 bbl/min slurry rates. The effective infinite conductivity fracture length is even slightly higher at 30 bbl/min [25].
The second step is the selection of the optimal treatment size. For every fluid/proppant system, there is an optimal hydraulic fracture length that gives the highest possible hydrocarbon recovery. The optimal fracture treatment is therefore calculated at this fracture length. The sensitivity analysis was run for different job treatment sizes as the study's primary goal is to analyze their effectiveness. The results are presented in Figure 3. As seen from the graph, the job with more than 160,000 kg of proppant will not add a significant gas production rate; on the contrary, the production rate will be slightly lower. For the bigger job treatment sizes, the propped fracture length, the infinite effective fracture length, and the fracture conductivity stay almost the same.

In the third step, the treatment pumping schedule is developed to inject the treatment fluid and proppant. The schedule reflects the volume of fluid based on the desired penetration and viscosity profile and the mass and proppant type based on the desired conductivity. A primary goal is to prevent events like screen-outs, which might be caused by insufficient width, pad depletion, slurry dehydration near the wellbore resulting from a high proppant concentration. The fracture area's proppant concentration depends on the rate of fluid loss from the slurry and the fracture width profile. The treatment's efficiency determines the proppant addition schedule that will achieve a specific slurry concentration in the fracture at the end of pumping—the grid output in Figure 6 results from the simulation of the novel fluid and glass beads. The average glass bead concentration based on the simulation results is 59 kg/m³. The perforations are depicted by the black crosses. From the graph, we can see that the gross length is 600 m, and the proppant cut-off fracture half-length is 150 m. The proppants are displaced relatively evenly, and the created fracture covers the net pay zone thickness.
The production prediction module was run to assess the effectiveness of the designed treatment. The production model is a single-phase Agarwal-Gardner type curve model with multiphase non-Darcy flow in the fracture. Figure 7 shows that the cumulative production of the stimulated well is almost three times the cumulative production of the unstimulated well

Simulation Results

Similar simulations were performed with the standard Aqua Master and Vistar fluid, using the glass bead proppants to identify the novel fluid's effectiveness. The same treatment schedule with the slickwater being used for the pad and over flash stages was performed. The fracture geometry parameters, as well as the post-treatment production enhancement, were investigated and compared. The Aqua Mater fluid results show that the proppant cutoff half-length is a little bit smaller compared to the novel fluid. The fracture will have the same geometry parameters, independent of the proppant type, and the production rate is similar. The results comparison shows that the propped cut-off half-length is higher with the Vistar fluid. Interestingly, in this case, the propped half-length of the fracture using the glass beads is equal to when carbo ceramics proppants are used. This could be because the glass beads are better displaced with the cross-linked fluid. To compare the results, it was decided to plot the propped half-length for all three designs with different fluid types with the glass beads being used as the proppant. The obtained geometry parameters are within expected ranges for the linear gelled fluid structures. The cross-linked fluid shows better behavior regarding better

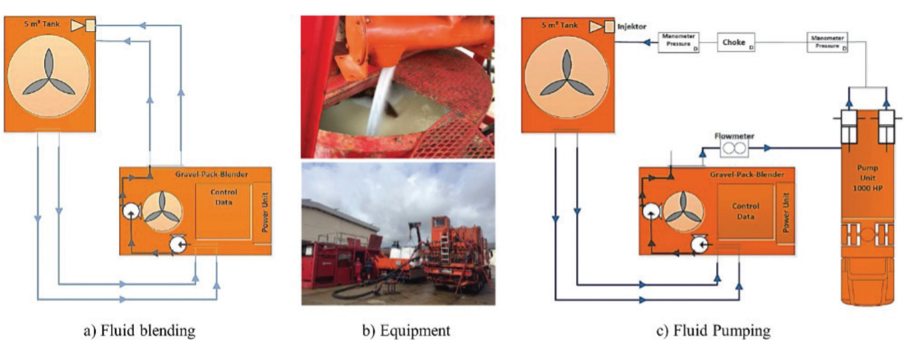

Fig. 8 Blending and pumping tests

Tab. 5 Density and pH-value of BEER fluid with and without K_2CO_3

Fluid composition	Density kg/m³	pH-Value @ 22°C
Tab water + 12 kg/m³ biopolymer	1000	7.6
Tab water + 12 kg/m³ biopolymer + 1,100 kg/m³ K2CO3	1400	11.9

Tab. 6 Test conditions for viscosity measurements

Pressure (MPa)	2.76
Continuous shear rates (s^{-1})	40, 100, 170
Test temperature (°C)	29, 70, 110
Geometry set	Rotor R1/Bob B5
Annulus (cm)	0.241
Bob radius (cm)	1.599
Bob height (cm)	7.620
Sample volume (ml)	52
Zero control (min)	every 50 minutes

proppant displacement and longer fracture half-length available for flow, and higher fracture conductivity, which is also confirmed by a literature review.

Field Trial

Blending and pumping tests

In a field test, carried out at the Fangmann Energy Services GmbH based in Salzwedel in Germany, the blending and pumping process for the BEER fluid and the miscibility of the fluid with the glass beads were tested.

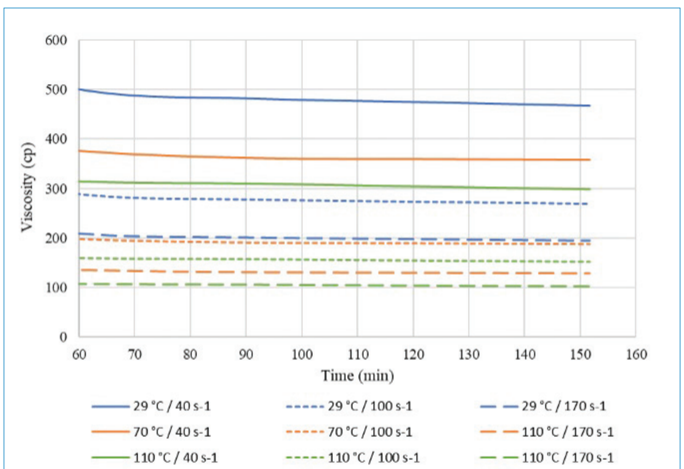

Fig. 6 Viscosity trend of the BEER fluid at different temperatures

The formulation of 5 m³ of tap water, 150 kg/m³ of K2CO3, and 6 kg/m³ of the biopolymer was tested.

First, the BEER fluid was blended in the 8 m³ tanks and then circulated through the blending system (Fig. 5, right). After adding the glass beads and ensuring that there were no problems within the blended fluid, the pump was added to the circulating system (Fig. 5, left). A blending and circulation procedure was started, to see if the proppants mix with the fluid and do not clog the pump or any part of the pumping system.

The sequence of mixing the components was investigated by preparing two mixtures each 2.5 m³, but in a different order. For the first test, the biopolymer was added first, followed by K_2CO_3, whereas the second one considered the opposite mixing order. The results showed that blending water first with K_2CO_3 and then adding the biopolymer will prevent the fluid from hydrating too quickly. Finally, silane-coated proppants were added to the BEER fluid and their performance was observed. The proppant could easily be added continuously to the fluid, up to a concentration of about 600 kg/m³, where the blending pumps started to lose prime for a certain duration. Looking carefully at the slurry, it could be observed that the beads mainly agglomerated within the fluid, and air bubbles were found to be often incorporated in the agglomerates. A portion of the beads popped to the gel surface to float like air bubbles, with a repellant behavior. Afterward, circulated slurry samples were diluted in the lab and the beads were washed out. It could be seen that about 5% of the coated glass beads floated on the water instead of sinking, which was expected. These glass beads were inspected using a microscope and air inclusions could be found. Based upon these results and further lab tests on the carrying capacity of the fluid, it is highly recommended to use the untreated glass beads for the operation. The coating repels the fluid and supports the incorporation of air bubbles within the fluid.

BEER fluid composition boundaries check

The fluid composition's mass concentration was checked in a sensitivity analysis to investigate the fluid's flexibility. The focus of the novel fluid is to be an environmentally friendly and clean alternative, to help to achieve a production enhancement at a much lower cost in comparison to conventional fluids. After checking the general properties of the fluid in the lab [44], the fluid was tested for its minimum and maximum boundaries, regarding temperature limits, limits in density, and constituent concentrations. Fluid tests are not only executed at static maximum reservoir temperature conditions, assumed to be 70°C, but also with lower temperatures as the fluid's surface temperature, assumed to be 29°C, and at an extraordinarily high temperature of 110°C. Besides, the reservoir rock is often cooled down during the stimulation process, as several 100 m³ of cold fluid are injected, thus low-temperature stability of the fluid is essential.

For accurate and near-field condition lab testing, the mixing water quality is crucial. Tap water and water samples of water, mostly used for well stimulations, were used. The BEER fluid's viscosity was tested with and without K_2CO_3, using the highest possible concentration of the biopolymer. The BEER fluid was prepared using the following procedure. While stirring at approximately 1,000 rpm, 6 g of the biopolymer was added to 500 ml of tap water. To prevent agglomerates, this procedure needed to be carried out very slowly (1.5 g/min). After 30 minutes of mixing, 550 g of K_2CO_3, which represents maximum solubility, was added. The fluid was mixed for a further 15 minutes. Table 5 shows the fluid composition, densities, and pH-values at a temperature of 22°C.

A high-pressure high-temperature viscometer was used to measure the viscosity trend of the fluid at the three temperatures. Table 6 summarizes the test conditions and the viscometer parameters.

In the field, the magnitude of the required viscosity is often overestimated. High viscosities lead to higher costs, increases the treatment pressure, and may reduce fracture conductivity as viscosity-raising chemicals often leave residues on the proppant pack and therefore reduce its permeability. The aim is to not increase the viscosity of the

Tab. 7 BEER fluid recipes 1 to 4

Component	Recipe BEER fluid 1	Recipe BEER fluid 2	Recipe BEER fluid 3	Recipe BEER fluid 4
H_2O	500 ml	500 ml	500 ml	500 ml
NaCl	100 g / 500 ml	150 g / 500 ml	0 g / 500 ml	0 g / 500 ml
K_2CO3	450 g / 500 ml	400 g / 500 ml	550 g / 500 ml	75 g / 500 ml
Biopolymer	6 g / 500 ml	6 g / 500 ml	6 g / 500 ml	6 g / 500 ml
Thickener	0 g / 500 ml	0 g / 500 ml	6 g / 500 ml	6 g / 500 ml

Tab. 8 BEER fluid recipes 5 and 6

Component	Recipe BEER fluid 5	Recipe BEER fluid 6
H2O (field)	500 ml	500 ml
K2CO3	75 g / 500 ml	50 g / 500 ml
Biopolymer	6 g / 500 ml	6 g / 500 ml
Thickener	6 g / 500 ml	6 g / 500 ml

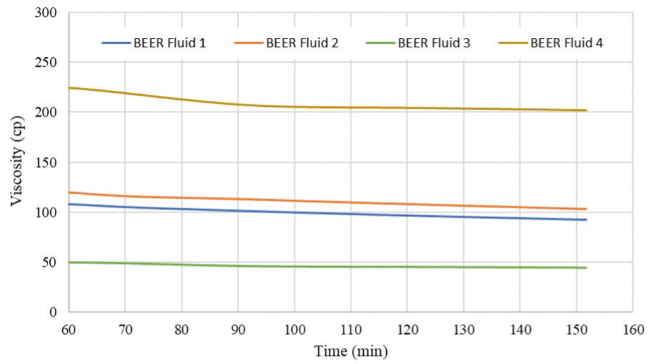

Fig. 7 Time-dependent viscosity of BEER fluids 1–4, as measured at 110°C and a shear rate of 170 s-1

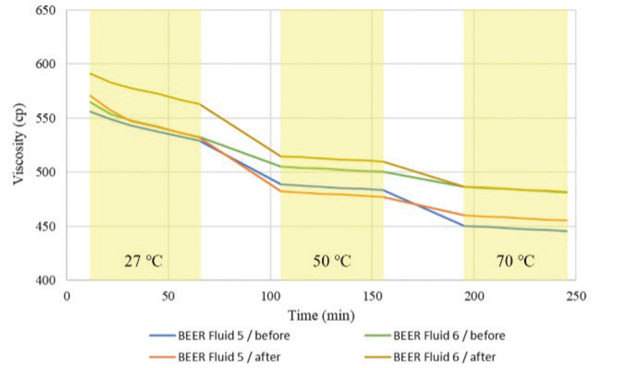

Fig. 9 Viscosity trend of BEER fluid 5 and BEER fluid 6 before and after storage at 27, 50, and 70°C and 100 s^{-1}

Fig. 8 Storage of BEER fluids in a metal container under ambient conditions for 24 hours

new fluid higher than necessary. Nevertheless, the maximum amount of dissolvable polymer is 12 kg/m³ and leads to the viscosity trend, shown in Figure 6. It shows that higher temperatures, higher shear rates and time, reduce the viscosity of the BEER fluid. The range of the viscosity is between 100 cp and 500 cp. The fluid does not drop below a viscosity of 100 cP at a shear rate of 170 s^{-1}, a temperature of 110°C, and 2.5 hours passed. This fact proves that the proppants can be transported even under harsh conditions.

Also, a mixture of a thickener and the biopolymer was tested – see BEER fluids 3 and 4 in Table 7. While stirring at approximately 1,000 rpm, the thickener was added followed by the biopolymer into 500 ml of tap water. This procedure was carried out very slowly (1.5 g/min) to prevent agglomerates. After 30 minutes of mixing, the appropriate amount of NaCl was added (only for BEER fluids 1 and 2). Next, the fluids were mixed for 15 minutes before adding K_2CO_3. After blending and mixing potassium carbonate, the viscosity was measured.

Figure 7 indicates that a decrease in the K_2CO_3 concentration and an increase in the NaCl concentration helps to increase viscosity slightly. Still, this difference in viscosity is too small to add NaCl to the BEER fluid recipe. Standard cross-linked hydraulic stimulation fluids can reach viscosities between 400–1,000 cP. Here it was not the goal to reach these high viscosities, as these fluids are often over-engineered.

BEER fluid 3 contains a thickener and a biopolymer. Figure 7 shows that this results even in a reduction of the viscosity in the case that the highest amount of K_2CO_3 is used to fulfill the 1,500 kg/m³ density requirement. In most situations, the required density is lower. BEER fluid 4 is made using the minimum possible amount of K_2CO_3, while adding the thickener. Here the addition of the thickener resulted in a viscosity increase, which is mainly caused by the lower pH-value, as less potassium carbonate is used. In conclusion, it can be recommended to use the thickener in combination with the biopolymer to get a higher fluid viscosity, but just in case of a not too high concentration of K_2CO_3.

In the next step, the storage capability of the BEER fluid was tested using two different recipes (BEER fluid 5 and BEER fluid 6). The viscosity was measured before and after the storage of the fluids in a metal container under ambient conditions for 24 hours. This test was carried out using a real field water sample. The test temperatures were reduced to 27, 50, and 70 °C. Table 8 summarizes the composition of the BEER fluid recipes 5 and 6.

Figure 8 shows the setup of the storage of the BEER fluids 5 and 6 in a metal container under ambient conditions for 24 hours. Before starting storage of both fluids with recipes 5 and 6, the initial viscosities at a shear rate of 100 s^{-1} and temperatures of 27, 50, and 110°C were measured using the HPHT-rheometer.

The viscosity measurements indicated again that the lower the K_2CO_3 concentration the higher the viscosity is. Depending on the formation to be treated, it may be possible to reduce the potassium carbonate concentration to 100 kg/m³ to get a higher viscosity. Figure 9 shows hardly any difference in viscosity before and after the storage duration of 24 hours. A storage effect can be neglected and fluid storage is possible after preparation.

The field water sample showed biological activity. For conventional fluids, the MPN (Most Probable Number Test) and the BART (Biological Activity Reaction Test) would have been mandatory to see if there are still

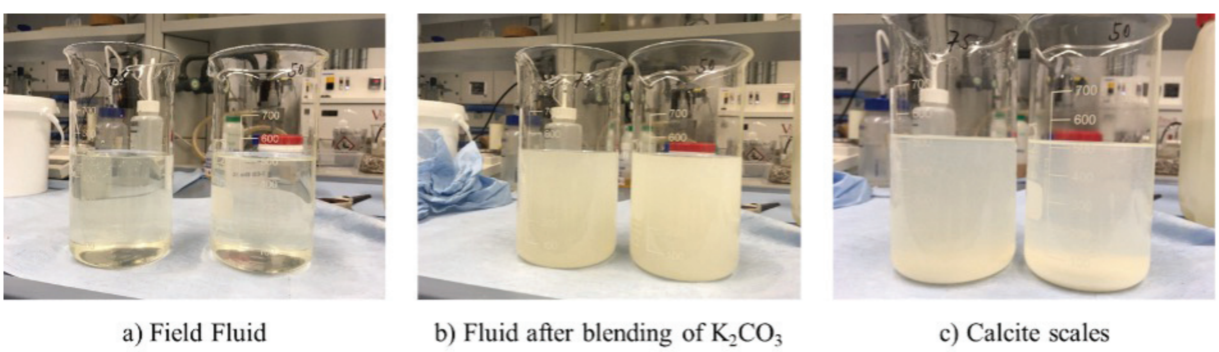

Fig. 10 Field water tests with K_2CO_3

bacteria in the fluid after blending. No biocides, MPN and BART are required for the proposed fluid, as the high pH-value, caused by blending K_2CO_3, kills all the bacteria in the fluid. The tests on storage of the BEER fluid for 24 hours, mixed with field water, showed that there is almost no polymer degradation, thus no bacteria in the fluid. No color change of the fluid or development of smell or any other anomalies were seen.

Another fluid sample was prepared in the lab using another water sample. The used water itself had a lower scaling tendency regarding calcite, which means the water is supersaturated. As calcite precipitation is usually delayed, a much higher saturation ratio is needed to create scale. This type of water would not cause scales under regular conditions in the field. Regarding the preparation of the BEER fluid, the water composition is critical. By mixing K_2CO_3 with this type of water, the pH-value changes from 7 to about 12, and additional CO_3 ions are added. Figure 10 indicates some scales after mixing, which could cause a permeability reduction in the reservoir. This fact confirms the importance of lab tests before field application.

Ecological Considerations

CO_2 Balance

To meet climate goals, which include the reduction of CO_2 emissions, also natural gas and deep geothermal energy are necessary. Especially natural gas is superior to other conventional energy resources in terms of CO_2 and particulate matter emissions. To produce unconventional natural gas and deep geothermal energy at some point the reservoir needs to be optimized and therefore stimulated to stay economical and productive. To not just consider technical and economic aspects, but to also check what environmental impact the BEER fluid could have in reducing greenhouse gases, a CO_2 balance was made. A CO_2 balance, also known as greenhouse gas balance, is used to calculate the carbon footprint of the production of different energy sources. The carbon footprint is gaining importance ground in the climate debate and also helps to show the positive environmental impact the BEER fluid could have.

For this ecological consideration, Germany was used as an example country and therefore data of the BVEG [7] and the "Umweltbundesamt" [36] were used to prepare the CO_2 balance. The BVEG delivers production data of oil and gas wells in Germany every month and also calculates a yearly production within Germany, but also shows how much oil or gas has been imported. In 2019 6.1 billion m³ of natural gas were produced within Germany and 28,6 billion m³ of natural gas were imported [7]. Germany has to report its yearly national emissions to the European Union and the United Nations. The emission factors out of this report [36] were used for the calculation of the CO_2 balance. It is still not possible to just use renewable energies instead of fossil energy sources, and an energy mix is necessary to not just reach the Paris climate agreement, but also to secure affordable energy security. Here it is important to see that domestic production can have a huge ecological impact. Domestic production in Germany decreases every year, also due to hydraulic stimulation restrictions, as most wells need stimulation to be able to maintain production rates, but also to increase their general recovery. So new technologies for increasing productivity and recovery like the BEER fluid are necessary to help to increase domestic production.

When comparing the CO_2 emission factor for the production of oil with the emission factor of the production of natural gas, it is about 1,000 times higher – 0,0001 kg/m³ vs. 0,1057 kg/m³. This shows that fossil energy resources need to be handled differently concerning CO_2 emissions and the concluding carbon footprint. Therefore, natural gas produced within Germany was compared to imported natural gas and deep geothermal energy as a renewable source, whose production can also be increased with help of a hydraulic stimulation using the BEER fluid, to show the importance of domestic production. Domestic production not just has a big impact on jobs within a country or e.g. the gross domestic production, but it has also ecological impacts. The CO_2 emissions of the production and processing of imported natural gas are five times higher than the CO_2 emissions of domestic natural gas.

Comparing deep geothermal energy as a renewable resource, which can also be produced within Germany, but is also in need of hydraulic stimulation techniques, shows another big difference in CO_2 emissions, as there are none. Even the release of gases dissolved within the hot geothermal water like H_2, CH_4, CO_2, or H_2S does not reach a concentration worth reporting. The operation of geothermal plants and geothermal heating plants in Germany does not increase emissions of gases having a climate impact. Even the own electricity requirements are covered by the grid [36].

Conclusions

This research work has shown the development of an optimized, economically friendly hydraulic stimulation fluid. The focus of the research was on developing a fluid, as simple as possible in composition, which fulfils all the needs in the field of hydraulic stimulation. In the article Bio Enhanced Energy Recovery – Development of a new Stimulation Technology [44] the product was studied, finding temperature limits and checking interactions and dependencies. This article concentrates on the pumping ability of the BEER fluid and the minimum and maximum boundary conditions in terms of component mass fraction, temperature, and proppant load.

The first question to be answered in studying the properties of the components and the interactions and dependencies already answered the part of what is the minimum amount of each ingredient, namely 6 kg/m³ Biopolymer and 100–150 kg/m³ of K_2CO_3. The viscosity of the BEER fluid can be further increased up to a value of 400 cp, by adding 12 kg/m³ of biopolymer, which is in the range of conventional stimulation fluids and represents the maximum dissolvable amount of this polymer. A mixture of 12 kg/m³ biopolymer and 12 kg/m³ thickener was tested together with 150 kg/m³ K_2CO_3 with field water. A viscosity of 500 cp at 70°C and 400 cp at 100°C was seen at a shear rate of 100 s^{-1}. This shows that the BEER fluid can also be customized for viscosities over 400 cp using the mentioned concentrations as a minimum. The K_2CO_3 concentration has a huge effect on the viscosity. As a result, high concentrations of potassium carbonate prevent the polymer swelling to its maximum. As a possible solution and to still be able to keep the density at its maximum, a part of the K_2CO_3 fraction can be substituted by NaCl. The results have shown that there is just an insignificant change in viscosity.

The substitution of oil production by clean natural gas and deep geothermal systems is necessary to meet the Paris 2020 goal of reducing CO_2 emissions. These resources often require the stimulation of the reservoir by hydraulic fracturing. The environmentally friendly BEER fluid meets the restrictions in terms of the fluid composition.

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