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The Application of Ultra-Lightweight Proppants to Cryogenic Liquid Nitrogen as a Fracturing Fluid: A Research Protocol

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Abstract
Introduction: Hydraulic fracturing has rapidly gained popularity in the last decade, emerging as the leading method of natural gas extraction in the United States. The practice remains controversial, however, due to the release of greenhouse gases from burning shale gas as well as the contamination of freshwater used in fracturing fluids. Although waterless fracturing fluids have been developed, including nitrogen, carbon dioxide, oil, and alcohol, their application has been limited due to either reduced fracturing power or safety, as well as environmental concerns. Recent research suggests that cryogenic liquid nitrogen may provide both a safe and environmentally-friendly alternative if a number of additional characteristics of its fracturing capabilities can be improved. Addition of ultra-lightweight proppants is a potential method of increasing the fracturing power of less viscous fluids. This research protocol aims to investigate the effect of ultra-lightweight proppant addition on the fracturing capabilities of liquid nitrogen.
Methods: Three ultra-lightweight proppants will be combined at differing concentrations with liquid nitrogen and applied to samples of shale rock under triaxial stress. A control trial will also apply liquid nitrogen without the addition of any proppant. Fracturing power, measured on the basis of fracture length, will be assessed following each trial.
Results: The results of these triaxial stress tests will provide measures of fracturing power for each proppant type and concentration combination.
Discussion: Analysis of these results will reveal whether the addition of ultra-lightweight proppants increases the fracturing capabilities of liquid nitrogen as well as identify the proppant type and concentration combination that affords liquid nitrogen the greatest fracturing power.
Conclusion: The effect of ultra-lightweight proppant addition on the fracturing capabilities of liquid nitrogen has yet to be explored. Implementation of this protocol will open more avenues of research into sustainable and efficient fracturing using liquid nitrogen.

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Keywords: hydraulic fracturing; natural gas; waterless fracturing; cryogenic fracturing; liquid nitrogen; ultra-lightweight proppants; green technology

Introduction

Hydraulic fracturing is a method of extracting natural gas from underground shale rock formations. Fracturing fluid, traditionally composed of water combined with gelling agents and proppants, is pumped into shale rock, creating fissures that allow recovery of natural gas as the fluid is subsequently extracted [1]. The use of hydraulic fracturing has increased dramatically since it was first implemented in 1947 [2], owing largely to the vast supply of untapped shale gas [3] and its lower economic cost compared to conventional methods of oil and coal drilling [4]. There are, however, several problems associated with the practice. Although burning shale gas releases less carbon dioxide than burning oil or coal, leakage of methane, the primary component of shale gas with established greenhouse gas properties, can make hydraulic fracturing even more harmful to the environment [5]. The use of large amounts of water in conjunction with toxic gelling agents also exacerbates the world's water stress, as well as risks contamination of groundwater if inadequately-treated waste fluid leaks from disposal sites [6]. Moreover, injection of waste fluid underground has been linked to seismic disruptions that increase the risk of earthquakes [7].

A method of addressing water consumption and contamination is to simply reduce or eliminate the use of water in fracturing fluids. Among carbon dioxide, oil, and alcohol-based candidates, nitrogen in particular has emerged as a promising alternative. An environmentally-friendly method, fracturing with pure nitrogen eliminates the need for toxic gelling agents and treatment of flowback while preventing formation damage, which occurs when components of the fracturing fluid react with minerals found in shale rock. Additionally, nitrogen does not contribute to greenhouse gas emissions, unlike carbon dioxide, or risk the explosions associated with oil and alcohol-based alternatives [8]. Nitrogen is currently used in the fracturing industry as an energized fluid or foam, which combines gaseous nitrogen (GN2) with water. Nitrogen mists, consisting almost entirely of GN2, are cleaner than their energized counterparts but are less widely applied due to a lack of viscosity, a key characteristic required to pierce deeper shale formations [9].

Increasing fracturing power can be achieved via the addition of proppants, which are solid materials such as sand and ceramic that enlarge and hold open fissures made by fracturing fluid [8]. Traditional proppants are too dense to be carried by pure nitrogen-based fluids, thus creating demand for ultra-lightweight proppants (ULWPs) that minimize density while maintaining the ability to withstand the high pressures within the wellbore. Nitrogen mist technology has already been improved with the addition of ULWPs, but its application remains restricted to shallow shale formations [10]. Cryogenic liquid nitrogen (LN2) is a novel alternative that has yet to be tested in conjunction with ULWPs. A more effective proppant-carrier in the liquid state, LN2 combined with ULWPs has the potential to greatly expand the application of pure nitrogen-based fracturing fluids. This study will test the effect of three ULWPs, at varying concentrations, on the fracturing power of LN2. Our proposal addresses the research question: What proppant type and concentration combination will allow LN2 to produce the longest fracture length in shale rock?

Methods

LN2 will be combined with three different ULWPs at three concentrations (0.05, 0.5, and 1.0 lb/ft^2) and applied to 8" x 8" x 8" samples of shale rock under triaxial stress of x: y: z = 1000: 1500: 2000 psi, for a total of nine trials (see Figure 1). An additional control trial will apply LN2 without any proppant under the same stress conditions. Fracturing power will be measured on the basis of fracture length, with deeper fractures indicating greater fracturing power. This triaxial stress test is based on a procedure established by Wang et al. [8] in which injection of LN_2 under triaxial stress of x: y: z = 1000: 1500: 2000 psi over two treatments produced the longest fracture length in shale samples. The three selected ULWPs have low density, allowing transport by low-viscosity fluids while maintaining the crush strength needed to increase fracture length (see Table 1); crush strength data were obtained from previous studies that tested the ability of the selected ULWPs to withstand pressure independent of combination with fluid [11, 12]. The lower the percentage of proppant crushed, the better its ability to withstand the applied pressure.

The first trial will mix LN2 with ULWP1 at a concentration of 0.05lb/ft^2, and apply the mixture to the shale sample at the aforementioned triaxial stress. The triaxial stress test will consist of two treatments. A borehole will be drilled into each sample, and the first treatment will circulate LN2 in the borehole at 15 psi for 40 minutes. The second treatment will inject LN2 at 450 psi three times for 15 seconds each, and the pressure at which fractures appear will be recorded. The second and third trials will follow the same procedure using concentrations of 0.5lb/ft^2 and 1.0lb/ft^2, respectively. The trials for ULWP2 and ULWP3 will be conducted in the same manner, while the control trial will proceed without addition of any proppant.

Results

Observation of fracture length following each triaxial stress test will provide a measure of fracturing power for each of the nine trials with proppant addition, as well as for the control trial applying LN2 independent of any proppant.

Discussion

Analysis of the fracturing power achieved in the nine trials with proppant versus the control trial will reveal whether the addition of ultra-lightweight proppants increases the fracturing capabilities of liquid nitrogen. Further comparison of the fracturing power achieved among the trials with proppant will identify the proppant type and concentration combination that affords liquid nitrogen the greatest increase in fracturing power.

A potential problem lies with the fact that it is unclear whether nitrogen will carry the ULWPs once temperatures in the wellbore induce its transition into the gaseous state. In the case of such a result, the protocol will have to be modified to better facilitate the maintenance of LN_2 in its liquid state.

If difficulties persist, it may be beneficial to test a different fluid alongside the trials with LN_2. Liquid carbon dioxide (LCO_2), for example, is easier to keep in a liquid state with its higher boiling point of 194.7K compared to the 77K of nitrogen [13]. LCO_2 also transitions into a supercritical fluid under wellbore conditions, suggesting slightly improved proppant-carrying capabilities compared to a gas [13]. However, the status of carbon dioxide as a greenhouse gas means that it may pose negative environmental impacts when released during fracturing. LN_2, as an inert gas that poses the least environmental risks, thus remains the preferred option to continue with this line of research.

Conclusions

Implementation of this protocol will further optimize LN_2 for widespread use as a fracturing fluid. New research questions that may arise following these results include how best to optimize conversion of GN_2 to LN_2 as well as maintenance of LN_2 in its liquid state. As discussed previously, it may also be beneficial to test alternative fluids such as LCO_2 alongside LN_2, in the event that vapourization of LN_2 greatly hinders its ability to carry the ULWPs. Additionally, the transition into synthetic material has led to the continuous advent of stronger and lighter proppants, creating the opportunity to re-apply this protocol in testing these new ULWPs. Future studies could also combine LN_2-proppant mixtures with emerging technologies such as the LN_2 jet [14], which increases fracturing power by injecting LN_2 at greater velocities.

With hydraulic fracturing now responsible for two-thirds of the natural gas produced in the U.S. [15], it is crucial to reduce the environmental impacts associated with the practice. LN_2 provides the most sustainable method of addressing water consumption and contamination thus far, conserving freshwater supplies while reducing ecosystem damage. Along with being environmentally-friendly, LN_2 options are highly economic given that GN_2 makes up 78% of air and air separation equipment can easily be used to compress GN_2 into LN_2 onsite, reducing transportation costs [9]. As such, research into LN_2 is highly relevant as the fracturing industry is forced to evolve amidst growing environmental concerns.

List of Abbreviations Used

LCO_2: Liquid carbon dioxide
LN_2: Liquid nitrogen
GN_2: Gaseous nitrogen
ULWP: Ultra-lightweight proppant

Conflicts of Interest

The authors declare they have no conflicts of interest.

Ethics Approval and/or Participant's Consent

This study did not require ethics approval and/or participant consent as it is a research protocol that has not been carried out to date.

Authors' Contributions

AA, AM, TZ: made contributions to the design of the study, drafted the manuscript, and gave final approval of the version to be published.

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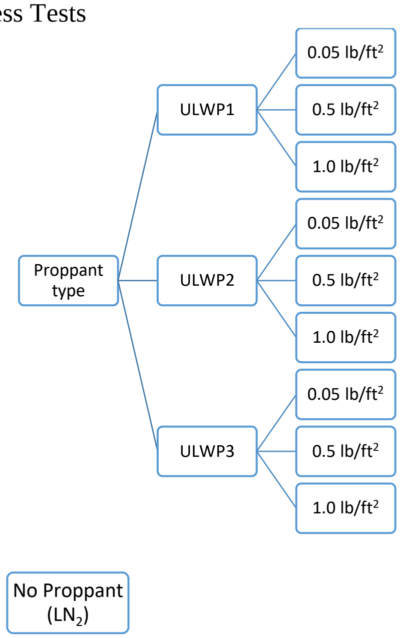
Figures

Figure 1: Triaxial Stress Tests



Tables

Table 1: Properties of Selected ULWPs

Ultra-Lightweight Proppants	Density (g/cm^3)	Composition	Literature Crush Strength
ULWP1	0.77	Ground walnut hull, impregnated and coated with resin, to increase strength	2.5%, under 15000 psi, 25°C
ULWP2	1.19	Porous, resin coated ceramic material	14%, under 15000 psi, 24°C
ULWP3	0.65	Polystyrene and modified silica fume	5%, under 7451.96 psi, 25°C

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