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Research Considerations for Foam Fracturing in Stimulation Development for Enhanced Geothermal Systems

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ABSTRACT

In regions where hydraulic fracturing is being considered for enhanced geothermal systems (EGS), and use of water is an issue, foam fracturing is an attractive option as a reduced water or waterless stimulation method. Although it has been shown to be an effective alternative in oil & gas production, foam fracturing has not yet been demonstrated in geothermal energy development. There are many challenges encountered in EGS. The reservoir may be located at great depth where earth stresses will be large and rock strength may be high. In addition, the viscosity of foam is higher than that of a pure single-phase fluid. Thus, the fracturing pressure will be increased substantially if a conventional fracturing routine is used. Moreover, fracturing in EGS systems may have more potential for induced seismicity.

A proactive approach is proposed to address this technical challenge by using pulsed injection in a current project, sponsored by the U.S. DOE GTO Waterless Stimulation Initiative. This approach enables the dynamic responses of rock structure to be utilized and a new cavitation-based material-removal mechanism to be explored for enhanced fracturing efficiency. It also offers an approach to mitigate fracturing-induced seismicity and the potential to control dynamic behavior of foamed fluids. Research considerations will be described for investigation of the above phenomena in foam fracturing for EGS stimulation development.

1. INTRODUCTION

Waterless stimulation has been explored for more than 40 years in oil & gas production. This technology has been tried historically in regions where formations are water sensitive or water is limited. It covers a wide range of mechanical, electrical, and chemical methods from fluid fracturing, electro-fracturing, cryogenic fracturing, to explosive and propellant fracturing. Review of these methods and techniques can be found in several publications (Gandossi, 2016; Moridis, 2017; Olasolo et al., 2016; Kohshour et al., 2017). Among these methods, pressurized fluid fracturing has been shown to be more attractive, including those based on aqueous foam. This is partly because of the extensive experience with hydraulic fracturing, which can be modified for the use with foams.

A foam consists of an immiscible, dispersed gaseous phase within a continuous liquid phase. The volume ratio of gas to liquid within the mixture is called quality and is typically used to classify foam and other immiscible gas/liquid mixtures. A quality value below approximately 64% is classified as an energized fluid; between values of approximately 64% and 95% is considered a foam; and above 95% is typically considered a mist (Faroughi et al., 2018). Foams offer many benefits for reservoir stimulation, including high proppant carrying capability, reduced formation damage, and improved flow back compared to gelled fracturing fluids. In fact, a large number of CO_2/N_2 foam-based fracturing jobs have been conducted in oil & gas fields in Canada and some in the U.S. (Jacobs, 2017; Reynolds et al., 2015). Most of these fracturing jobs were carried out in under-pressured reservoirs and a few in over-pressured reservoirs where fracturing fluids were injected with pressure as high as 4,110 psi (28 MPa) at 12,000 ft (3.7 km) depth (Harris et al., 1984; Warnock et al., 1985). On the other hand, the application of fracturing using pure CO_2 or N_2 is relatively limited because these methods fail to meet requirements for conventional reservoir stimulation such as the ability to transport proppants.

In the regions where geothermal development is being considered but use of water is problematic, foam fracturing is a potential option. However, foam fracturing under EGS relevant conditions has not received much research attention to date. Many factors, including suitable surfactants, field injection schemes, foam stability, foam rheological behavior, and rock response to foam stimulation must be better understood before foam fracturing can be properly evaluated for the temperatures and pressures of interest for EGS. This paper will describe relevant considerations and initial efforts to investigate the prospects for foam fracturing in EGS applications.

2. BACKGROUND

There are several important issues that are unique and need to be addressed for EGS. Prospective EGS reservoirs are expected to be significantly deeper than prior field experience in oil & gas bearing rocks. Typical rock strength in geothermal applications is generally higher than oil & gas applications and target bottom hole temperatures, generally greater than 180 ^oC, are also higher. For a vertical well in which one of the principal stresses is parallel to the borehole axis and is not the minimum, the breakdown pressure p_b can be expressed as (Valko and Economides, 1997),

$$p_{b,upper} = 3\sigma_x - \sigma_y - p + T \; with \; \sigma_y \leq \sigma_x, \qquad \text{when there is no fluid penetration} \tag{1a}$$

$$p_{b,lower} = \frac{3\sigma_x - \sigma_y - 2\eta p + T}{2(1-\nu)}, \eta = \frac{\alpha(1-2\nu)}{2(1-\nu)}, \qquad \text{when there is fluid penetration} \tag{1b}$$

where σ_x and σ_y are horizontal stresses, p is the pore pressure, T the tensile strength, α the Biot constant, and υ the Poisson's ratio. If the initial earth stresses mainly result from the overburden, then

$$\sigma_x = \sigma_y = \sigma_h = \frac{\nu}{1-\nu}\sigma_z, \quad \sigma_z = \rho g h \tag{1c}$$

where ρ is the density, g the gravity acceleration, and h the depth. Eq. (1) indicates that with the increase of earth stresses and rock strength, the breakdown pressure will increase accordingly. Fluid penetration into the rock matrix reduces the breakdown pressure. Conversely, fracture initiation pressure increases with the increasing viscosity and fluid compressibility (Christopher, 2015; Jia et al., 2018). Fracture fluid mechanics analysis indicates that, for a Perkins-Kern-Nordgren (PKN) fracture model, the net well pressure $p_{n,w}$ (i.e., difference between well pressure and far field stress) for sustaining injection can be expressed as (Valko and Economides, 1997),

$$p_{n,w} = \left(\frac{80}{\pi^2}\right)^{1/4} \left(\frac{E'^4 \mu i^2}{h_f^6}\right)^{1/5} t^{1/5}, \tag{2}$$

where E' is the plane strain elastic modulus, μ the viscosity, i the injection rate, h_f the fracture height, and t the injection time. The enhancement of well pressure for hydraulic fracturing due to increasing viscosity of the driving fluid can be seen easily. This model can be used for numerical simulation of fracture using conventional fluids (Ribeiro and Sharma, 2013). However, it does not take into account the rheological behavior and compressibility of foams, which can differ significantly from gelled fluids.

There are at least the following technical challenges existing for aqueous foam-fracturing in a geothermal application:

- Surface blending and pumping machines need to work at a pressure level as high as 10,000 psi. This is because the dispersed phase is generally pumped on the surface in liquid state that is maintained at a substantial level of pressure (Harris et al., 1984; Warnock et al., 1985). The capability of pumping liquids, CO_2, or N_2 under such high pressure remains to be demonstrated.
- Response of surrounding rock mass in fracturing job with the enhanced injection pressure is unknown. Especially, seismicity can result from such process as faults in the formation are lubricated and pressurized. The seismic events were reported during many hydraulic fracturing and waste water injections (Olasolo et al., 2016; McGarr, 2014). The stimulation of the geothermal site in the suburb of Basel in Switzerland, for example, induced a seismic event with moment magnitude, Mw of 3.2, which unfortunately led to the abandon of the project. When the EGS well goes deeper, and foam injection pressure becomes higher; the response of rock can be more dynamic, and more energy will be accumulated in a fracturing job. Currently, no data is available in EGS regarding how seismicity is affected by foam injection. However, intense microseismic events induced by foamed water fracturing in a gas/oil field were observed (Duhault, 2012).

In the following sections, we will focus on several important aspects of foam design and injection to address the challenges mentioned above related to foam fracturing in the laboratory.

3. LABORATORY SETUP FOR INVESTIGATION OF FOAM STIMULATION

3.1 N_2 foam fracturing

A notable laboratory study on foam fracturing is credited to Wanniarachchi et al. (2018). They investigated the fracture behavior and permeability response of siltstone using foam made of N_2 and water under various confining pressures at room temperature. The foam generation subsystem consists of a gas line and a liquid line. The N_2 gas was supplied by a gas cylinder and the flow was controlled by a Cole-Parmer gas flow controller that is capable of controlling flow from 0.05 to 5 l/min at 1 MPa maximum line pressure. The water flow was driven by compressed air and controlled by a Cole-Parmer liquid controller, at 0.05 to 1 l/min, with a maximum line pressure of 0.8 MPa. The gas and liquid flows are set at individual rates according to the pre-determined quality of foam with same pressure level, pass through the respective check valves and are mixed by an inline foam generator. An ISCO 260D syringe pump was used to inject the foam with a maximum pressure of 50 MPa.

Wanniarachchi at el. (2018) used a specimen of diameter 54 mm and height 90 mm containing a blind hole of diameter 4 mm drilled into the half height. The axial compressive stress and confining pressure were set at 20 and 10 MPa respectively, in order to control the fracture in the axial direction. Liquids both foamed at 70% quality and un-foamed were injected at 10 ml/min. The breakdown pressure of foam injection was 27 MPa, which is higher than that of water, 21 MPa. The higher breakdown pressure was attributed to the high viscosity of foam as seen from Eq. (2). The foam injection took about 625 sec to fracture the rock, which is much longer than that of water injection. At the specified rate, a longer injection time means a larger injection volume. The higher volume of N_2 foam injection was attributed to a high compressibility of the foam compared to water. The overall water consumption was about 5% less considering 30% water used in the foam. A substantial amount of foam was believed to have penetrated into the rock matrix, which might be mitigated by increasing the injection rate.

3.2 Air foam fracturing

Another important study of foam injection was performed by Young and Graham (1999). In a series of experimental studies, they developed a controlled foam injection technique that can be used as an alternative to explosive blasting for secondary rock breakage and concrete stripping. The foam was made of air and water in a specific quality with foaming surfactants.

The injector consisted of a foam reservoir, a gas tube arranged co-axially inside the reservoir, and a reverse acting puppet (RAP) valve. The release of high-pressure gas induced the lift of the RAP valve and further triggered the foam injection into the injection barrel. The preparation of injection involved pre-drilling a hole over the rock surface with diameter of 41 to 51 mm. Young and Graham (1999) used foam with a quality less than 50%. They believed that, when the foam expanded into the developing fracture, the foam quality would increase with a concordant increase in viscosity. The injection system was able to remove about 0.24 m^3 of rock from the surface of a tunnel, which was a dense compact type of rocks with high mechanical strength. The controlled foam injection had been shown to be very energy efficiency and environmentally friendly. However, the pressure level used in the rock breaking system was not disclosed. Prefilling the foam reservoir took a long time, and filling the injection barrel also consumed a significant amount of foam before it could pressurize the rock. This was because of small displacement per stroke, which ranged from 0.04 in^3 (0.6 ml) for the liquid pump to 1.20 in^3 (19.7 ml) for the gas booster pump. The output pressure of these pumps could be as high as 15,000 psi (103 MPa).

In a later study, Young (2002) proposed a new foam generator that used hydraulically driven boosters and pumps. Such system with low area ratios between input and output pistons would allow foam mixing and delivery at a level of 0.5 to 1 liter in a single cycle.

3.3 CO_2 foam fracturing

There are no laboratory studies reported on CO_2 foam fracturing. However, CO_2 foam stimulation was previously demonstrated in oil & gas field application (Harris et al. 1984; Warnock et al., 1985). The CO_2 foam with 70% quality was shown to have successfully stimulated a zone at 12,000 ft (3.7 km) depth using a treating pressure greater than 4,110 psi (28 MPa). The CO_2 foam was shown to be quite stable at a downhole temperature of 188°C. A significant rate of gas/ oil production was achieved. The absence of laboratory studies may be related to safety concern with CO_2 as discussed extensively by Harris et al. (1984) and Warnock et al. (1985), whilst air and N_2 are explored much more widely.

CO_2 foam has some appealing features. In particular, the foam with supercritical CO_2 has a density close to water and significantly higher than that of N_2 or air foams. Therefore, a much higher hydrostatic pressure can be obtained, which relaxes pumping requirements at the wellhead for deep stimulation. The rheology of CO_2 foam was tested and modelled by Reidenbach et al. (1986) along with that of N_2 foam. Recently, an increasing number of research studies were conducted on testing and characterization of CO_2 foam as a response to increased interest in oil & gas, and CO_2 sequestration applications (Ahmed et al., 2018).

3.4 Potential research direction

Laboratory research on foam fracturing is limited, particularly at the temperatures and pressures of interest for EGS. Such research is critical to the design of foam injection approaches and the evaluation of foam fracturing effectiveness. Further laboratory study of foam fracturing is needed to better understand foam stability, pumping characteristics, and stimulation effectiveness for EGS representative conditions, including dynamic rock response. There are several subsystems involved in this report: foam generation, injection, pressure cell and environmental conditions.

3.4.1 Foam generation

Generally, there exist two types of procedures for foam generation.

- One is to mix the gas and liquid phase to a defined volume ratio at low pressure and then pressurize the foam (Wanniarachchi at el., 2018). A defined quality of foam is obtained by controlling flow rates of each phase. The flow rate control under lower pressure can be implemented easily. The downside for this procedure is that the pump would be required to handle the foam at a range of qualities.
- Another approach is to drive each phase to a target pressure and then mix to the defined volume ratio (Young and Graham, 1999). In this case, the flow rate is to be controlled under high pressure, and the flow meter and controller will have to be designed to meet high-pressure requirements. The associated design criteria and fabrication cost will increase accordingly. The advantage of this procedure is that the pumps for liquids and gas booster are well developed and commercially available.

The selected procedures shall be applicable to foams made of gases of interest. A comparison study is necessary to justify the feasibility and effectiveness of the approach for a given laboratory condition.

3.4.2 Foam injection

Foam injection can be performed with two types of control methods: pressure control and rate control. Such controls are available in some commercial systems like the ISCO 260D syringe pump (Teledyne ISCO, 2018). Pressure regulators and flow controllers can be implemented to achieve such controls alternatively. In a pressure control mode, the flow rate starts at a very high value, which will fall and recover, and increase rapidly when the fracture occurs. Under flow control, the pressure starts to build up, develops to a specific level, and drops rapidly as the fracture is imminent. In both cases, the flow rate under consideration can be very low (Wanniarachchi at el., 2018). Lab fracturing tests using other media such as water, oil, and liquid N_2 are usually conducted at flow rates between 1 and 20 ml/min (Christopher , 2015; Li et al., 2015), which is relatively low compared to those used in fracturing jobs in the field (25 bpm, or 3,972 l/min, Valko and Economides, 1997).

Measurement and control of flow in low flow conditions is challenging. There are several measurement methods available, including those based on Pelton wheel, thermal conduction, Coriolis effect, and others. The Coriolis method directly measures mass flow and is more accurate and faster than other approaches like that in thermal mass flow meters. Moreover, flow density can be obtained at the same time. This can be an important feature in the foam injection for controlling and verifying the quality of foam. Some commercial flow meters, such as the mini Cori-Flow series of Bronkhorst (2018), can provide measurement in various mass flow ranges. For example, model M14 has a range from 100 to 10,000 g/h (1.667 to 166.7 ml/min for water) with a pressure rating of 200 bar or greater with a customized design. The Quantim series of Brooks Instrument (2018) also provide similar flow meters and controllers.

In a conventional fracturing job, injection would be pursued in flow rate control mode (Valko and Economides, 1997). The fracturing jobs are mainly conducted in a static manner. It has been observed that breakdown pressure increases significantly with the use of high viscosity liquids like CO_2 foam. The increased breakdown pressure presents substantial challenge to fracture control. Historically, the control of energy release of hydraulic fracturing has also been related to induced seismicity. Zang et al. (2013) studied rate profiles of step-wise increase and pulse using numerical analysis. They observed that the pulsed profile released the accumulated energy intermittently and thus could significantly reduce the peak energy level.

The introduction of pulsed injection into foam fracturing, as will be pursued in future, needs a substantial R&D effort. In laboratory setting, the pulsed injection can be performed alternatively in pressure control mode with a combination of selected pressure regulators and control valves. Lessons learned from such studies can serve as an input for the next stage development.

3.4.3 Confining pressure and environmental temperature

EGS is generally expected to occur at depths greater than 4 to 5 km with temperatures more than 180^{o}C (Olasolo et al., 2016). Most descriptions of EGS target granite rock with low permeability and porosity. At an averaged depth 4.5 km, the vertical and horizontal stresses could be as high as 111 and 37 MPa for representative in situ stress states. Such levels of confining pressure and temperature can be implemented using high-pressure cells equipped with heating capability. The main issue with the high pressure and high temperature is their effect on the breakdown pressure. As can be seen from Eq. (1), the breakdown pressure will be dominated by the confining pressure at great depth, especially when the pore pressure is absent in hot dry rock. It can reach up to 92 MPa, if the two horizontal principal stresses are considered equal and 18 MPa is taken as the tensile strength of granite. A further complication is the pressure variation when heating is introduced. The experiment can be carried out under two conditions: constant pressure, or constant quality. A test procedure is required to control foam characteristics as environmental conditions vary.

4. DOWNHOLE INJECTION SYSTEM

4.1 Existing injectors for downhole applications

The downhole injection system proposed by Harrigan et al. (2013) features two chambers. The first chamber of injection fluid is separated from the second chamber of working fluid by a piston. The working fluid is employed to apply pressure to the piston to direct injection fluid to the formation. A flow regulator is used to regulate flow of the injection fluid. The system may be a “wireline' tool suspended within a wellbore or attached to the lower end of a wired pipe string. The injection fluid is injected into the formation through an injection tool, which usually includes pump, injection line and probe. The probe is designed to establish communication between the system and formation to either inject fluid into formation or withdraw formation fluid into the system. The downhole system can be used as a sampling-while drilling (SWD) tool or for any dedicated analysis. In various oil & gas exploration operations, it is beneficial to have information about the subterranean formations penetrated by a wellbore. For example, certain formation evaluation schemes may include measurement and analysis of the formation pressure and permeability. Flow control is desired when injecting fluids into the subterranean formation between measurements. However, traditional pump systems are limited in operation by the range of flow rates or the ability to control the flow during injection. Their system can provide the capability for such operation and control needs.

Another system was proposed by Rhodes and Welch (2005) for the downhole injection of chemical into a well. The system injects the fluid through capillary tubing by using a surface pump and downhole injection valve. It includes an upstream and a downstream check valve linked in series. The upper check valve has an adjustable spring bias that can be pre-set for required working pressure. The lower check valve has a fixed bias and protects the injection valve from the unwanted backflow. The backflow makes it very difficult to regulate or assure a consistent flow or continuous volume of chemical injection. The proposed system can resolve such issue. The downhole system can be used for well treatment, particularly those wells which produce hydrocarbons, to ensure well production and operability of downhole equipment.

Newton (2001) also proposed a fluid dispersing valve. The valve is designed such that the carrier fluid constantly flushes the valve’s moving parts, and the valve is sealed from the dispersed fluidic substance to prevent from jamming the moving parts. The fluidic substance disperses out a housing through arranged openings when the pressure of the fluidic substance exceeds a threshold pressure. The valves can be used in the irrigation of farmland and manufacturing processes such as in petrochemical industry.

4.2 Pulsed injection

4.2.1 Rotary shuttle valve

A motorized rotary shuttle valve has been utilized recently to create the pressure pulsation and cavitation under equivalent EGS condition. The cavitation is exploited to fracture rocks or brittle materials in a controlled way with reduced damage to structures. The concept and design of system was explained in related U.S. patents (Wang et al., 2016, 2017). The valve body is composed of three sections: the back section is a housing that hosts an electric motor, the center is a high-pressure chamber with the rotating shaft passing through, and the frontal is an expanded chamber that includes a perforated wheel rotating at a defined speed. After entering the chamber, the fluid will pass the perforated wheel and discharge into the frontal chamber. The abrupt change of flow path results in a large pressure fluctuation near the shuttle valve. The generated pressure fluctuation serves as a pulsed pressure applied to a rock surface. At the same time, the fall-and-rise of pressure tends to create and destroy cavitation bubbles, and produce shockwaves and micro-jetting near the rock surface (Ren et al., 2010; Ren et al., 2012). These processes can fracture and remove material particles from the rocks in various scales of sizes.

4.2.2 Solenoid valve

Pulsed injection for fracturing job may be achieved using concepts developed for fuel injection of engine systems because of the similarity of pulsed profiles between the two. In the fuel injection of a diesel engine (Bosch, 2004), the efficient combustion requires precise dose control under very high fuel pressures c.a. 200 MPa. A needle valve is generally used, which is driven characteristically in linear direction. In a typical injection system, hydraulic circuit is included to produce pressure difference along the needle. It is the pressure difference that controls the lift and return of the needle. The actuation is achieved by a solenoid coil. When energized, it moves the actuator stem up, opens the ball vale in a control volume, and de-pressurizes the control volume. The series of actions creates the pressure difference and lifts the needle momentarily. The return springs are incorporated in both actuator and needle valve sections to return the needle back to the seat when the coil is un-energized. The high-pressure fuel is supplied by a common rail that is driven by a positive displacement pump for multiple engines.

4.2.3 Piezo valve

Piezo valve uses piezoceramic multilayer actuator for actuation. The piezo valve with hydraulic circuit usually has a configuration very similar to that of a solenoid valve (Kim et al., 2005). When the actuator is energized, actuator stem pushes the control valve, which opens the return line and de-pressurizes the control volume. As a result, the pressure difference along the needle is created. There have been a quite number of variants proposed (Rueger et al., 2003; Rauznitz et al., 2005; Niethammer et al, 2005; Kobayashi and Hattori, 2006). In the design of Rueger et al. (2003), a double acting control valve is included working with the piezo actuator and a hydraulic amplifier to control the pressure in control chamber. The use of piezo actuator enables multiple injections of fuel in an engine cycle and more controllable rate profile because of fast response of piezo actuation. As the fuel is combusted more effectively, both fuel consumption and emission can be reduced significantly.

In parallel, the concept of direct acting piezo valve has been developed in the last decade or so. As implied, the piezo actuator acts on the needle directly, but not via the pressure difference created by hydraulic circuit. The removal of hydraulic circuit makes control easier and enhances the response of valve substantially. In an U.S. patent, Stier (2002) described a system in which a tubular piezo actuator is energized to remove the sealing force applied by a restoring spring, inducing injection event. Another system in the same patent utilizes an expanded nozzle head that is pushed off the valve seat by the piezo actuator through a lever plate. The restoring and pressure strings are used for the return of valve when the actuator is de-energized. Both systems are design to work in a mode of energizing-to-inject.

Delphi introduced a direct acting piezo valve into market about ten years ago (Schoppe et al., 2008). The system uses a piezo stack with a hydraulic amplifier to apply actuation force directly on the needle. The piezo system has been shown to perform much better than the one with solenoid valve. The Delphi valve is designed to de-energize to inject. In other words, the needle is pushed against the seat all the time unless it is de-energized. The actuator may draw a significant amount of current, but the design comes with strategies to address the issue (Dober et al., 2008). The peak rate of pulsed injection can reach as high as 50 g/s in a pulse length of about 1.5 ms, depending on fuel pressure in common rail.

Nouraei (2012) later developed a piezo injector, which includes a metal disk as a motion invertor and amplifier. As a result, the system can work in a mode of energizing-to-inject. An actuator housing of 30 mm inside diameter (ID) and 156.5 mm height was used to accommodate the actuator, and the upper and lower interface assemblies. A Ti-6Al-4V alloy disk measured with 31.75 mm in diameter and 1 mm in thickness served as the motion inverter. The disk has been demonstrated to be able to amplify the output of piezo stack 1.4 times.

4.3 Potential research direction

The foam fracturing has been shown to have a relatively high breakdown pressure compared with those using single-phase liquids because of the inherent high viscosity. An actively-controlled downhole injection appears to be very important, especially considering that the fracturing job in EGS stimulation is pushed much deeper than ever before (more than 4 to 5 km). Such great depth of source strata has not been seen in the oil & gas fields. The great depth, pore-pressure-less, and high-strength rocks would signify themselves a substantial high level of breakdown pressure involved.

Conventionally, hydraulic fracturing is carried out by setting a flow rate, injecting a pressurized flow into wellbore or tubing and monitoring the pressure profile. All controls if available occur at the wellhead. The injection control technology needs to be advanced, including downhole injector and a range of procedures to control the magnitude of rate and rate profile shape. A carefully-dosed injection design and an effective implantation can reduce water consumption and, at the same time, minimize side effects such as seismicity. The pulsed injection may be a good candidate approach to serving this purpose.

Several noticeable and important benefits can be obtained from pulsed injection.

- First, pulsed injection enables the dynamic response of rock structure to be explored. An amplified displacement of fracture surface can be achieved by tuning the rate profile at the injection site to target frequency range. The introduction of dynamic injection opens enormous opportunity for fracturing applications as the fracturing fluid can be used much more efficiently.
- Second, the local pressure pulsation produces cavitation. The collapse of cavitation bubbles near a solid surface generates shock wave and micro jets that dynamically impinges the solid. The imploding pressure on the surface from the collapses of cavitation bubbles can be as high as 700 MPa. While being a threat to safety of water systems, the cavitation is considered here as a material removal mechanism to develop fractures as desired in energy source extractions (Ren et al., 2010; Ren et al., 2012; Wang et al., 2016, 2017). The cavitation-based mechanism offers additional avenue to fracturing rocks using a reduced amount of fracturing fluids.
- Third, pulsed injection mitigates the fracturing-induced seismicity. For a pulsed or cyclic injection, the energy accumulates and releases intermittently, and induced seismic scale can be lower than that of the continuous injection (Zang et al., 2013). Although such benefit has been suggested by numerical simulation, the pulsed injection has not been realized in the field.
- Fourth, the high shear-rate arising from pulsed injection has the potential to reduce the viscosity of foams. It was shown that for a given quality of CO_2 foam, for example, the apparent viscosity decreases with the increasing shear-rate (Harris et al., 1984). Thus, the developed pressure in fracturing can be lowered for a given fracture length, and the penetration and diffusion of pressurized fluids into rock formation can be increased.

As previously discussed, the downhole injection systems developed in the past were mostly for chemical remedy or geological exploration. They apparently lack the controllability of rate profile. The downhole injection valve that enables the delivery of pulsed rate profile remains as a technical gap. The rotary shuttle valve and piezo valve have been shown to be quite promising to meet such need. A comparison of the two approaches is given in Table 1. It should be noticed that the pressure loss of a downhole injection valve is not to be significantly high, although the valve body is subjected to high-pressure level of pressure loading around 92 MPa. Such pressure difference provides the flexibility for valve trim design (Skousen, 2004).

Table 1 Comparison of two candidate injection systems

Type	Advantages	Disadvantages
Rotary shuttle valve	It is a rigid design with proven technology and could be easily adapted to high injection rate.	It needs a mechanical driver and concept remains to be validated in EGS.
Piezo valve	Based on solid-state technology, it is compact, flexible for rate control, and proven in fuel injection at high levels of frequency, pressure, temperature.	Reliability remains to be demonstrated in EGS.

5. FOAM CHARACTERIZATION

5.1 Experimental methods

Reidenbach et al. (1986) studied rheological properties of foams made of N_2 and CO_2 as part of their earlier efforts to support foam fracturing in oil & gas fields (Harris et al., 1984; Warnock et al., 1985). A recirculating-flow pipe loop was used to collect flow data. The loop was built of 0.305” (7.75 mm)- ID stainless steel tubing. The liquid phase was pumped into the loop from a 5-gal pressure vessel by a metering pump. The loop was filled with liquid to a pressure 1000 psi (7 MPa). The gas phase was added into the loop through an orifice and the excess fluid was released using a backpressure regulator. Fluid flowed through a mass flowmeter and specific gravity was read, which allowed the foam quality to be adjusted on-line. A glass inspection gauge was installed for visual inspection of the flow. A differential pressure transducer with 0 to 25 psi (0 to 0.2 MPa) range was used to measure the pressure drop across a 120” (3.05 m) section of 0.305” (7.75 mm) -ID tubing. The fluid flow within the loop was driven by a gear pump. Such recirculating loop was also used by Harris and Reidenbach (1987) to study the rheology of N_2 foam at temperatures up to 300^{o}F (149^{o}C).

Sun et al. (2014) described a loop used in an experimental study of CO_2 foam. It includes two plunger pumps to pressurize the liquid and gas lines before mixing. The foam quality is obtained by adjusting the pump flows of CO_2 and liquid. The foam passes a heating section before entering the test sections for rheology and heat transfer study. The loop can generate foam at temperature above 120^{o}C at pressure above 60 MPa. The whole pipeline is about 20 m long with a heating section of 12 m. The rheology testing section is configured with tubing of 8 mm - ID, 16 mm – outside diameter (OD), and 1 m length. After the test sections, fluid is decompressed by a throttle valve before entering the cyclone separator. The CO_2 is then separated and discharged to the environment and the liquid phase is expelled from a buffer container. These authors mentioned that the system is not really a recirculating loop as the residence time of flow in the loop is about 35 to 75 s.

Gu and Mohanty (2015) used a recirculating loop in their study on polymer-free N_2 foam. The loop is very similar to that of Reidenbach et al. (1986) and Harris and Reidenbach (1987). A heating jacking is installed in one section of loop to heat the foam. A desired quality is achieved by continuously monitoring the density of foam using a densitometer when N_2 gas is being introduced. The test section has a diameter of 12.70 mm and a length of 15.24 m. The loop can test foamed fluids at temperature around 155°F (68°C), pressure of 2000 psi (14 MPa), and shear rate up to 2000 s^{-1}.

Ahmed et al. (2018) described a pressurized foam rheometer developed by Ametek Chandler Engineering (Model 8500, Broken Arrow, OK) in their study of supercritical CO_2 foam fracturing fluid. The main foam loop is contained in an oven where the foam can be subjected to elevated temperatures at high pressure. The test section includes a CCD camera attached to the view cell, Coriolis mass flow meter, positive displacement pump, foam generator, gas booster pump, and backpressure regulator, and Hastelloy C276 tubing. The tubing of the test section has 7.75 mm -ID and 3.05 m length. The system can test a foamed fluid to pressure 3000 psi (21 MPa), temperature 350°F (177°C) and shear rate 1000 s^{-1}.

5.2 Viscosity and stability of foams

As mentioned, earlier work in this field was performed to support the foam fracturing activities in the Red Fork formation and Haynesville strata (Harris et al., 1984; Warnock et al., 1985). Reidenbach et al. (1986) studied the viscosity of N_2 and CO_2 foamed fluids. The liquid phase contained 0.5% of an anionic surfactant and 0 to 0.48% of hydroxypropyl guar (HPG) as a gelling agent. The foams were tested under 1000 psi (7 MPa) with various shear rates at room temperature. The authors used Herschel- Bulkley (HB) model to characterize the viscosity of the foams. The foams became thinning at high shear rates. The apparent viscosity increased with the increasing quality and increasing HPG concentration. There was a remarkable similarity in the apparent viscosities of the N_2 and CO_2 foamed fluids. A further experimental work (Harris et al., 1987) studied the N_2 foamed liquids at temperatures from 75 to 300°F (24 to 149°C). High quality foams hold the viscosity better at high temperatures than non-foamed gelled fluids. The observation showed that high gelling agent concentrations do not improve foam stability. Rather, high temperature stability depends on surfactant type and concentration.

When the quality exceeds the wet limit, there is a transformational change in the bubble shape from spherical to polyhedral. The interface energy between the dispersed and continuous phases increases substantially, and the system becomes increasingly unstable. The bubble coarsening, coalescence and drainage occur in the foam mixture. These phenomena degrade the stability of foams and finally result in the breakdown of the system. Many procedures and methods have been investigated to bring the system under control. One of the most popular ways is to add surfactants to reduce the surface tension as discussed by Reidenbach et al. (1986) and Harris et al. (1987). There are several other approaches, for example, adding non-Brownian solid particles to enhance the viscoelasticity, adding Brownian nano-particles to retard the drainage, adding hydrophobic colloidal or nano-particles as stabilizing agent to increase the film dilational viscoelasticity, and so on (Faroughi te al., 2018).

The addition of surfactants can reduce the surface energy, slow down the temporal evolution of the structure, and delay the collapse, thus creating a more stable foam. The foam stability can be strongly affected by temperature and pressure.

- At high temperatures, coarsening and coalescence become faster. The rate of drainage also increases with temperature because of the reduced viscosity of film liquids.
- The effect of pressure on foam stability depends on the surfactant type. In the cases of C16 alpha olefin sulfonate (AOS) and fluorinated betaine, the stability of foams increases with the operating pressure, whilst fluorinated betaine with oil resulted in a reduced stability of the foam with pressure (Holt et al., 1996). The composition of the gaseous dispersed phase also affects the foam stability. A high-pressure static-stability analysis in closed system carried by Harris (1995) on foams with 70% quality found CO_2 foam was more stable than N_2 foam.

The use of surfactants has been also shown to enhance the viscosity, especially at high bubble volume fraction (Gu and Mohanty, 2015).

5.3 Effects of shear stress, shear rate, pressure, and temperature

The microstructures have an important effect on the mechanical responses of the foams, including films, Plateau borders, and bubble rearrangement. Upon shearing, foam generally show viscoelastic behavior. For small applied stresses, Plateau criterion (i.e., films meet at angles of 120°) is always satisfied and deformation is reversible. The surface tension provides strain resistance in a solid-like behavior, and the imposed surface energy is released upon removing the stress. At high stress, bubbles start to deform instead of just re-aligning. The films shrink or thicken. The films are in contact such that Plateau criterion is no longer satisfied, and surface area between constituents and consequently the surface energy increases. The unfavorable structure transforms into another static equilibrium configuration with lower surface energy; namely, the foam shows a transition from solid-like to liquid-like behavior (Saint-Jalmes and Durian, 1999). The yield stress depends on surface tension, volume of the dispersed fraction or quality, and aging. The foam in fluid-like regime behaves as strongly shear thinning fluids.

The rheological behavior of energized fluid and foams is affected by the stress conditions such as shear rate and the flow geometry like tubing and fracture. Such behavior can be studied by using a capillary number, defined as ratio of viscous forces to surface tension (Faroughi et al., 2018). The relative viscosity of energized fluids and foam increases with the volume fraction of dispersed phase, depending on the capillary number. At small capillary number, surface tension and capillary stress are sufficient to resist deformation. The bubbles remain spherical and relative viscosity increases with volume fraction of bubbles. At higher capillary number, bubbles become severely deformed and act like shear banding zone. In this case, the relative viscosity depends on the viscosity ratio of dispersed phase to ambient phase, and the resisting force is mainly controlled by the shear within the dispersed phase. A smaller effective viscosity than that of the ambient fluid can be seen in the energized fluid where bubbles are dispersed in a viscous liquid.

The effective viscosity of foams increases with pressure (Cawiezel and Niles, 1987; Gu and Mohanty, 2015). This effect can be due to the increases in gas density and gas viscosity, and a change in bubble configuration, size distribution (Herzhaft et al., 2005).

The high temperature at downhole conditions affects the rheology and stability of foams more significantly than the pressure does. The increase in operating temperature increases the drainage and coalescences, and the surfactant becomes inoperable. With the excess of tension, the interfacial energy becomes very large and liquid film mobility increases. As a result, foam deformation is accelerated, and the effective viscosity is reduced as can be seen for N_2 and CO_2 foams (Harris et al., 1987; Gu and Mohanty, 2015; Ahmed et al., 2018). The temperature effect on the effective viscosity of foam strongly depends on the type and concentration of surfactants used. The viscosity of viscoelastic surfactant (VES) foams is affected more significantly than that of AOS foams (Cawiezel and Niles, 1987; Gu and Mohanty, 2015). The composition of dispersed phases also affects the effect of temperature on the effective viscosity of foams. At the high temperatures, the viscosity of N_2 foams remain higher than that of CO_2 foams (Hutchins and Miller, 2005).

5.4 Future research direction

In oil & gas fields, fracturing liquids need to fracture the formation for stimulation, to transport proppants to downhole and further into fracture, and to clean up after job for production. These functions usually demand a liquid to possess contradictory features. The proppant transport requires a high viscosity, but for fracturing, a lower viscosity is better. Use of polymer as a gelling agent promotes the viscosity, but it complicates after-job clean-up. Foam has been shown to be better in terms of proppant transport and clean-up, considering its high viscosity and gas-driven clean-up mechanism. Foam has been also shown to be able to protect the fracturing liquid from leakage thanks to the osmotic pressure effect (Faroughi et al., 2018). Owing to the unique viscoelasticity, foam behaves more solid-like in a fracture inlet and liquid-like near the fracture tip, both of which are very appealing features for proppant transport and fracturing.

In EGS, the proppant transport and after-job clean-up haven't received as much attention as those in oil & gas fields. However, the effect of high temperature on the stability for a foamed liquid appears to be one of the most important issues that need to be addressed. A hydraulic fracturing job can take more than 2 to 3 hours in oil & gas production (Valko and Economides, 1997). A foam used for the fracturing should survive long enough for the job to be completed. Lifetime of foams is affected significantly by temperature. The EGS will reach a great depth that oil & gas fields have not seen with a high temperature (> 180°C). The understanding of foams and effect of surfactants at such level of temperatures need to be developed. The effect of pressure on the stability of foam seems to be secondary, based on the pressure ranges tested. But, the response of foams at the pressure level equivalent to EGS (92 MPa) is unknown. Extension of lifetime of foams for high temperature application by using alternative approaches such as addition of nanoparticles may be explored if the available methods cannot meet the requirements.

The effective viscosity data is essential for design of a fracturing job. As discussed, the viscosity depends on stress conditions (shear stress and shear rate), pipe geometry (pipe size), foam history (aging), foam composition (dispersed phases, surfactants and other additives), and operating conditions (temperature and pressure). There has been a volume of viscosity data published for various foams. Apparently, these data sets were generated in specific conditions, for example, temperature and pressure. The extrapolation of the observation into the working range of EGS needs to be carefully considered, for which data analytics may be helpful. The temperature range for retaining viscosity may be extended by using surfactants along with gelling agents, for which some systems are commercially available (Linde, 2015). Eventually, there shall be a performance and cost analysis to screen the candidate fracturing liquids.

There are three common gaseous phases that can be potentially considered for EGS application including N_2, CO_2 and air. Compared to N_2 and CO_2 foams, the research on air foam is relatively limited. A comparison of the foams based on the three gaseous phases is provided in Table 2. The behavior of these foams under the EGS operating conditions remains to be studied.

The current experimental setups, mostly dedicated to oil & gas production research, are shown to be limited in terms of either temperature range or pressure range. Experimental system for test and characterization of foams under condition relevant to that of EGS also remains to be developed.

Table 2 Comparison of candidate foams

Gaseous phase	Advantages	Disadvantages	Refs.
CO_2	It may be naturally available or obtained from coal power/ fertilizer plants, high viscosity/ density; there are some experiences in gas/oil fields.	It faces logistics challenge; needs to be shipped to the site, for which recycling of CO_2 is ongoing now to address the issue; CO_2 may be hazards.	Moridis (2017); Kohshour (2018); Jacobs (2014); Harris et al. (1984); Warnock et al. (1985).
N_2	It may be produced on site as N2 is available in air; there are some experiences in gas/ oil production.	Low temperature of liquid N_2 may damage casing or tubing; mostly limited to low formation.	Moridis (2017); Kohshour (2018); Jacobs (2014); Reynolds (2015).
Air	It can be made on site; it was used once in foam fracturing in mines.	Limited data are available.	Young and Graham (1999).

6. CONCLUSIONS

Very limited laboratory research is available for foam fracturing, especially of CO_2 foam. Most of the experimental studies were carried out in a single-pass loop with various foam generation routines; either mixed to pressurize or pressurized to mix. The injection can be conducted in pressure control or rate control mode. The injection procedure is generally quasi-static; the procedure for cyclic injection with pressure/ rate shape definable needs to be developed. The treatment pressure can be affacted by temperature and confining pressure; when the temperature increases, pressure and quality may vary and complicate the characterization of foam fracturing.

The foam fracturing has been shown to have a relatively high breakdown pressure compared with those using single-phase liquids because of the inherent high viscosity. An actively-controlled downhole injection appears to be very important, especially considering that the fracturing job in EGS stimulation is pushed much deeper than ever before. The injection control technology needs to be advanced, including downhole injector and a range of procedures to control the magnitude of rate and rate profile shape. The pulsed injection may be a good candidate approach for this purpose. The downhole injection systems developed in the past were mostly for chemical remedy or geological exploration. They apparently lack the controllability of rate profile. The downhole injection valve that enables the delivery of pulsed rate profile remains as a technical gap. The rotary shuttle valve and piezo valve have been shown to be quite promising to meet such need.

The fracturing liquids need to fracture the formation, to transport proppants to downhole and further into fracture, and to clean up after job. These functions usually demand a liquid to possess contradictory features. The proppant transport requires a high viscosity, but for fracturing, a lower viscosity is better. Use of polymer as a gelling agent promotes the viscosity, but it complicates after-job clean-up. Foam has been shown to be better in terms of proppant transport and clean-up, considering its high viscosity and gas-driven clean-up mechanism. The stability, mechanical and rheological behaviors of foams depend on quality, compositions, foam history, pipe geometry, stress condition, operating temperature and pressure. Foams are currently tested using a recirculating loop and the data generated mostly to target oil & gas applications. Extrapolation of the observation into the EGS case needs to be carefully considered. The advanced testing and characterization approaches remain to be established for screening of the candidate foams and development of a new generation of foams for high temperature and high pressure EGS applications.

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