OR/15/066 Hydraulic fracturing

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This chapter describes the relevant stages of the hydraulic fracturing process. Several overviews of hydraulic fracturing are available in the literature; including API, 2009; Arthur *et al.*, 2008[1]; Broomfield & Donovan, 2012[2]; CSUG, 2010[3]; King, 2012[4]; Mair *et al.*, 2012[5]; Reinicke *et al.*, 2010[6]; US EPA, 2010[7]; etc. Hydraulic fracturing is the process by which a liquid under pressure causes a geological formation to crack open. The process is also known as 'HF', 'fracking' or 'fracing', but is referred to as 'hydraulic fracturing' in this report. In order to be able to understand the mechanical controls on hydraulic fracturing it is important to have a detailed knowledge on the injection process itself. This allows us to pinpoint areas of the process which are less well understood and where research should be focused. An increase in research into these areas will ultimately result in the process becoming more refined and lead to either higher productivity or a more cost effective process and reduce the likelihood of environmental contamination.

Depth of interest

The first consideration in assessing the hydraulic fracturing process is the depth range that it is likely to occur. Andrews (2013)[8] state that productive shale gas tends to occur at depths greater than 1,000 metres. This figure comes from Charpentier & Cook (2011)[9] who state that whilst gas is found at shallower depths, the lower pressure experienced results in low flow rates. The Geological Society of London states that most shale gas plays occur in the depth range of 2,000 to 5,000 metres (Geol. Soc., 2013)[10] and that depths should be typically less than 3,500 metres (Geol. Soc., 2011[11]). Fisher & Warpinski (2012[12]) report hydraulic fracturing data for the United States. This shows that existing operations have occurred between 4,500 ft and 14 000 ft in Woodford shale, 4,500 ft to 9,000 ft in Marcellus, and 3,000 ft to 13 000 ft in Eagle Ford. This gives a total depth range of 1,000 to 4,300 metres. The Energy Information Administration (US) reports a maximum depth of hydraulic fracturing of 5,000 metres (US EIA, 2013[13]). Therefore, it is expected that shale gas exploitation in Europe will be limited to the 1,000 to 5,000 metre depth range.

State of stress

Knowing the depth range that hydraulic fracturing is bound allows an estimate to be made of the expected stresses experienced by shale at depth. The magnitude and direction of the principal stresses are important in hydraulic fracturing because they control the amount of pressure required to create and propagate a crack, the direction of the crack, and the crack shape. The stress a rock experiences is dictated by the weight of the overlying rock, with additional stresses created by tectonic movements. Generally, in sedimentary sequences a total vertical principal stress gradient of 23 MPa/km can be assumed (Zoback, 2010[14]). This suggests that total vertical stress (δV) is likely to range between 23 and 115 MPa in European shale gas operations. As well as a vertical stress component, shale at depth will be subject to horizontal stresses. Zoback (2010)[14] reports that the minimum horizontal stress (δh) component cannot be less than 0.6 δV. Most sedimentary sequences that include shale occur in extensional basins where the maximum horizontal stress (δH) is the intermediate stress component (i.e. $\delta V > \delta H > \delta h$). Therefore the three principal stress components are likely to be defined as 23 < δV> 115 MPa; 13.8 < δh> 115 MPa; 13.8 < δH > 115 MPa.

Predicting pore pressure range with depth is more complex. Generally, a hydrostatic pore pressure (u) can be defined by the weight of a water column equal to depth, giving a pore pressure gradient of 10 MPa/km. Therefore pore pressure is likely to range between 10 and 50 MPa in European shale gas operations. However in basins that are bound by low permeability barriers, such as shale cap rock or faults with high clay content, deformation can result in a raised pore pressure, referred to as overpressure. Overpressure can also be observed in shale gas units, Charpentier & Cook (2011)[9] report that it is a desirable attribute in shale gas reservoirs.

The introduction of pore-fluid under pressure has a profound effect on the physical properties of porous solids (Hubbert & Rubey, 1961[15]; Terzaghi, 1943[16]). In a saturated porous system, the fluid supports some proportion of the applied load, creating fluid-pressure (u), which acts in the opposite direction to load lowering overall stress exerted through mineral grains. The addition of u lowers available stress by an amount that is proportional to the pore pressure. The law of effective stress thus dictates that strength is determined not by confining pressure alone, but by the difference between confining and pore-pressures. In simple drained tests, u remains constant and the observed effective stress is similar to the applied load. Conversely, if the pore-fluid system is closed, u rises in proportion to the applied load as pore space is reduced, significantly lowering the overall effective stress. Thus, the mechanical response of rocks to applied load is significantly affected by the ability of fluids to drain. Many rocks have been shown to follow the law of effective stress, including shale (Handin *et al.*, 1963[17]; Kwon *et al.*, 2001[18]). Kwon *et al.* (2001)[18] showed that the effective pressure coefficient χ was equal to 0.99 ± 0.06 for Wilcox shale. This value is indistinguishable from unity and demonstrates that the law of effective stress is obeyed in this particular shale formation. The poroelastic effect (after Biot, 1941[19]) is added to the law of effective stress to account for the partial transfer of pore-pressure to the granular framework. Therefore at the target depth range for shale gas the effective stress is likely to range between 3.8 and 65 MPa, assuming no overpressure.

Direction of drilling

Hydraulic fracturing requires the drilling of a borehole to the target depth. Advances in drilling techniques have meant that it is now possible to drill both vertically and horizontally (created by deviating a vertical well until horizontal). The advantage to horizontal drilling is that there is a larger surface area in contact with the target formation, meaning there is the potential for a greater reservoir drained volume achieved and increased flow of hydrocarbons into the well. Hydraulic fractures tend to propagate perpendicularly to the direction of least principal stress, following the direction of maximum principal stress (API, 2009[20]). As a result, horizontal wells are drilled in the direction of the minimum principal stress. Experience in the Marcellus Shale in Pennsylvania shows that horizontal wells may extend up to 3,000 (King 2012)[4] metres laterally from the well pad (Arthur *et al.*, 2008[1]). Therefore the total length of the well could be in the region of depth + 3,000 m, therefore up to 6,000 metres in length.

Stages of shale gas extraction

Shale gas extraction consists of three stages (Mair *et al.*, 2012[5]):

- **Exploration.** A small number of vertical wells (perhaps only two or three) are drilled and

fractured to determine if shale gas is present and can be extracted. This exploration stage may include an appraisal phase where more wells (perhaps 10 to 15) are drilled and hydraulically fractured to characterize the shale; examine how fractures will tend to propagate; and establish if the shale could produce gas at commercially viable rates. Further wells may be drilled (perhaps reaching a total of 30) to ascertain the long-term economic viability of the shale.
- **Production.** The production stage involves the commercial production of shale gas. Shales with commercial reserves of gas will typically have a gross thickness greater than 50 metres thick and will persist laterally over hundreds of square kilometres. In North America, shales often have shallow dips in relatively structurally simple basins when compared to many in Europe. Vertical drilling would tend to pass straight through them and access only a small volume of the shale. Horizontal wells are likely to be drilled and fractured. The drill bit can be deviated to run horizontally or at any angle in order to maintain the wellbore within the target horizon.
- **Abandonment.** Like any other well, a shale gas well is abandoned once it reaches the end of its producing life when extraction is no longer economic. Sections of the well are milled out and filled with cement to prevent gas flowing into water-bearing zones or up to the surface. A cap is welded into place at the surface and then buried.

Description of the hydraulic fracturing process

There are several stages to the drilling process as outlined below.

Initially a drill string is used to drill a shallow borehole through the surface layers and casing is inserted into the borehole and cemented in place. This stops the inflow of groundwater and also prevents the borehole from collapsing. The well is then drilled to a greater depth below the base of the local groundwater and further casing is cemented into place. In some cases at this stage a ‘cement bond’ geophysical log may be run to inspect the integrity of the casing and cement. After this the well will be drilled to its target depth and the entire well will be cased and cemented. In some cases the very end of the well may be left uncased[21], this is called an ‘open hole’ and can be done to minimise formation damage when the hydraulic fracturing process begins. As stated above, exploration wells will tend to be drilled vertically, whereas production wells are most likely to be deviated to horizontal. Once drilling is complete, the drill string is extracted.

Geophysical logs may be run before or after the final casing is inserted. Wireline logs are very useful for gaining data of target areas which will be the most suitable for the hydraulic fracturing process. There are many techniques which can be employed downhole, such as gamma ray logs, ultrasonic logs, temperature and density logs. Often a combination of these techniques will be used to gain as much information about the formations as possible. These techniques can output properties such as porosity, lithology, acoustic impedance (used to understand the structure of the formation) and permeability. Once this data has been interpreted and the areas identified which the reservoir engineers believe will be the most productive then the hydraulic fracturing process may begin; this is used to increase the local permeability around the well to enhance hydrocarbon flow back to the surface.

Once the well has been drilled, lined, and geophysically logged, the shale formation can be stimulated. The process of hydraulic fracturing is complex and can be split into several key stages, although it must be noted that these stages may be different at each specific site. The process described here is that of multi-stage fracturing; large horizontal wells are split into isolated segments to fracture separately.

1. **Perforation:** The cementation and lining of the well means that the inside of the well is isolated from the host geology; this is highly desirable above the shale play where potable water aquifers may be present. This stage of the hydraulic fracturing process allows connection of the well to the shale play at the desired depth. Shaped charges (explosives) are pushed down the cased well to the desired well depth. Detonation of these charges perforates the well at given orientations and also results in finger-like fractures or weak points forming in the shale surrounding the well that can be up to 1” (2.5 cm) in diameter and extend 24” (60 cm) into the formation. Pre-perforated liners have been used in some cases; however in-place perforation provides more accuracy for creating perforations at the desired location.
2. **Isolation:** Initially, perforation occurs at the section furthest away from the well head. This section is then isolated from the rest of the well using a packer.
3. **Stimulation:** High pressure fluid is then injected into the packered off section of the well. This high pressure fluid has the purpose of increasing the pore pressure in the local area of the perforated borehole, which eventually overcomes the tensional strength of the formation, resulting in a network of fractures forming. Fracturing fluid normally consists of water with a range of additives to facilitate the fracturing process (*see* Fracturing fluids). A proppant is forced into the fractures by the pressured water and holds the fractures open once the water pressure is released. Sand proppants are often used with this stage repeated several times using different size mesh of sand particles to prop open fractures of different sizes; synthetic polymer beads, or ceramic proppants may also be used. Stimulation may occur over the time-scale of tens of minutes to a few hours, depending on the designed fracture size and volume of the proppant to be placed.
4. **Flushing:** Further injection takes place to flush out excess proppant and any other objects which may obstruct flow.
5. **Multi-stage perforation:** The packer is then deflated and pulled further back towards the well head to begin the perforation and injection stage again.
6. **Flow back:** Once all the packered sections of the well have been stimulated the packers are removed and the fracturing fluid is allowed to flow back towards the surface, leaving the proppants behind to keep the hydraulic fractures open. Gas will now be free to flow back towards the surface.

In recent years effort has been made to increase fracture populations through various advanced hydraulic fracturing techniques. These include the Zipper and Texas Two-Step methods. In the Zipper technique two horizontal wells are stimulated simulateously to maximize stress perturbations near the tips of each fracture (Rafiee et al., 2012[22]). This technique has been adapted into the Modified Zipper technique where fractures are initiated in a staggered pattern, creating a more complex fracture pattern (Rafiee et al., 2012[22]). In the Texas Two-Step method (Soliman et al., 2010[23]) repeat stimulation is performed in an alternate sequence. In conventional stimulation, as described above, the well can be considered as stimulations sites numbered 1 to 10. Conventionally stimulation occurs in order of 1, 2, 3, etc. With Texas Two-Step the stimulation sequence is 1, 3, 2, 4, 6, 5, etc. Any change in fracturing sequence alters the stress in the area between fractures and activates stress-relieved fractures, which can create a complex network of fractures connected to the main hydraulic fractures (Rafiee et al., 2012[22]). This method has been shown to create a more complex fracture network (Roussel & Sharma, 2011[24]).

The complete fracturing process may be repeated when the flow of hydrocarbons begins to decrease, necessitating the well to be re-stimulated. Re-fracturing is typically carried out when the production rates have declined beyond the expected reservoir depletion rate (ICF, 2009[25]). In examples from the Barnett shale, wells were re-stimulated when production declined by between 50–85% of the original production rate (ICF, 2009[25]). However, experience in the states has shown that re-stimulation is likely to be infrequent; either once every 5–10 years, if at all (NYSED, 2011[26]).

Economics will drive the decision on re-stimulation.

The process of hydraulic fracturing will be tailored for each different geological formation. The properties of the formation and the *in situ* pressure conditions will govern much of the process, such as the fluid injection pressure and the number of stages needed. Shale formations can be heterogeneous and anisotropic so the physical properties of the shale will need to be defined accurately in order for the hydraulic fracturing process to be appropriately managed and as cost effective as possible.

Fracturing fluids

Fracturing fluid normally consists of water with a range of additives to facilitate the fracturing process and increase fluid flow in the borehole and formation. In some shale gas plays in the US such as those with water-sensitive components (for example, swelling clay) and under-saturated reservoirs, gelled fracturing techniques are used (US EPA, 2010b[27]).

Within the injection fluid is often several chemicals in low concentrations; these are often not disclosed in the U.S. however in certain European states, they must be disclosed to authorities. These chemicals are often a mix of dilute acid, a friction reducer, biocides and an oxygen scavenger aimed to modify fluid mechanics to increase performance of the fracturing fluid or for purposes such as the prevention of corrosion to the well pipes and retardation of bacterial growth. The NYSDEC (2011)[28] state that fracture fluids typically consist of about 98 per cent water and proppant (usually sand, but other granular materials can be used) and 2 per cent additives; this figure is the largest estimate of additive proportion; in the UK about 0.2% additive has been used (see below). Table 1 summaries the types of chemicals that may be used within the fracturing fluid.

Water used during stimulation often derives from surface or groundwater sources, supplemented by recycled water from previous hydraulic fracturing cycles. Significant quantities of water may be used, depending on well characteristics. Vertical shale gas wells typically use approximately 2,000 m^3 of water; horizontal wells require approximately the same amount of water per stage of stimulation (US DOE, 2009[29]). In the European context, Cuadrilla Resources Limited estimate usage of 12 000 m^3 per horizontal well in the UK (ECCC, 2011[30]), in the Netherlands at Boxtel it has been stated 1,000 m^3/h per 1–2 hour stage was used, resulting in 9,000–29 000 m^3 of water used (Broderick *et al.*, 2011[31]). For the hydraulic fracturing carried out by Halliburton at the Lubocino-1 well in Poland, 1,600 m^3 of fluid was used.

Cuadrilla in the UK have stated that <0.05% of the fracturing fluid is made up of chemical additives (Stamford & Azapagic, 2014[32]), meaning that 6 m^3 of chemicals are used per well based on an estimate of 12 000 m^3 of fracture fluid used. Cuardrilla disclosed the chemical additives used as: 1). Polyacrylamide friction reducers (0.075) suspended in a hydrocarbon carrier; 2). hydrochloric acid (0.125%); and 3). biocide (0.005%), used when the water provided from the local supplier used in the hydraulic fracturing needs to be further purified (DECC, 2014[33]).

Table 1 Fracture fluid additives (From NYSDEC, 2011[28]; Broomfield & Donovan, 2012[2])

Additive type	**Description of purpose**	**Examples of chemicals**
Proppant	'Props' open fractures and allows gas/fluids to flow more freely to the well bore.	Sand (sintered bauxite; zirconium oxide; ceramic beads)

Acid	Removes cement and drilling mud from casing perforations prior to fracturing fluid injection and provides accessible path to formation.	Hydrochloric acid (3–28%) Muriatic acid
Breaker	Reduces the viscosity of the fluid in order to release proppant into fractures and enhance the recovery of the fracturing fluid.	Peroxydisulfates
Bactericide/biocide/ antibacterial agent	Inhibits growth of organisms that could produce gases (particularly hydrogen sulfide) that could contaminate methane gas. Also prevents the growth of bacteria, which can reduce the ability of the fluid to carry proppant into the fractures.	Gluteraldehyde 2,2-Dibromo-3-nitrilopropionamide
Buffer/pH adjusting agent	Adjusts and controls the pH of the fluid in order to maximise the effectiveness of other additives such as crosslinkers.	Sodium or potassium carbonate Acetic acid
Clay stabiliser/control/KCl	Prevents swelling and migration of formation clays which could block pore spaces thereby reducing permeability.	Salts (e.g. tetramethyl ammonium chloride) Potassium chloride (KCl)
Corrosion inhibitor (including oxygen scavengers)	Reduces rust formation on steel tubing, well casings, tools, and tanks (used only in fracturing fluids that contain acid).	Methanol Ammonium bisulfate for oxygen scavengers
Crosslinker	Increases fluid viscosity using phosphate esters combined with metals. The metals are referred to as crosslinking agents. The increased fracturing fluid viscosity allows the fluid to carry more proppant into the fractures.	Potassium hydroxide Borate salts
Friction reducer	Allows fracture fluids to be injected at optimum rates and pressures by minimising friction.	Sodium acrylate–acrylamide copolymer Polyacrylamide (PAM) Petroleum distillates
Gelling agent	Increases fracturing fluid viscosity, allowing the fluid to carry more proppant into the fractures.	Guar gum Petroleum distillates
Iron control	Prevents the precipitation of metal oxides which could plug off the formation.	Citric acid
Scale inhibitor	Prevents the precipitation of carbonates and sulfates (calcium carbonate, calcium sulfate, barium sulfate), which could plug off the formation.	Ammonium chloride Ethylene glycol

Solvent	Additive that is soluble in oil, water and acid-based treatment fluids which is used to control the wettability of contact surfaces or to prevent or break emulsions.	Various aromatic hydrocarbons
Surfactant	Reduces fracturing fluid surface tension thereby aiding fluid recovery.	Methanol Isopropanol Ethoxylated alcohol

For conventional hydraulic fracturing, the fracture pressure gradient is typically 9–27 kPa/m. For instance, for a typical 2,400 metre conventional well, this would correspond to approximately 50 MPa and pressures would generally be below 65 MPa.

It should be noted that assuming a 5 inch diameter well with a 6 km length, the volume of the well alone is approximately 75 cubic metres (or approximately 50 cubic metres for a 4 inch diameter well).

Knowledge gaps and recommendations

This chapter has described the hydraulic fracturing process. It is recommended that all work within the M4ShaleGas project should make reference to the processes employed during hydraulic fracturing. All modelling and laboratory experiments should be conducted in a manner that is representative of the process employed in the field by the shale gas industry.

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