Chapter

A Review of Fracturing Technologies Utilized in Shale Gas Resources

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Abstract

The modern hydraulic fracturing technique was implemented in the oil and gas industry in the 1940s. Since then, it has been used extensively as a method of stimulation in unconventional reservoirs in order to enhance hydrocarbon recovery. Advances in directional drilling technology in shale reservoirs allowed hydraulic fracturing to become an extensively common practice worldwide. Fracturing technology can be classified according to the type of the fracturing fluid with respect to the well orientation into vertical, inclined, or horizontal well fracturing. Depth, natural fractures, well completion technology, capacity, and formation sensitivity of a shale reservoir all play a role in the selection of fracturing fluid and fracturing orientation. At present, the most commonly used technologies are multi-section fracturing, hydra-jet fracturing, fracture network fracturing, re-fracturing, simultaneous fracturing, and CO_2 and N_2 fracturing. This chapter briefly reviews the technologies used in shale reservoir fracturing.

Keywords: hydraulic fracturing technology, unconventional reservoirs, fracturing fluids, well fracturing

1. Development of fracturing technology

In the past four decades, various technologies have been developed and implemented to improve the production from shale gas formation as it is a commercially feasible source of energy. Hydraulic fracturing is a technique applied to enhance hydrocarbon extraction from subsurface geological formations by injecting a fluid at pressure higher than formation pressure to crack open the hydrocarbon formation rock. The hydraulic fracturing technology is not new; first experiment was conducted in 1947, and the first industrial implementation was in 1949 [1]. Hydraulic fracturing has, since then, been used for stimulating unconventional reservoirs and enhancing oil and natural gas recoveries. The first operation of fracturing treatment was performed by gelled crude, and later gelled kerosene was used. By the end of year 1952, many fracturing treatments were carried out by processed and live crude oils. This type of fluids is low-cost and permitting greater volumes at lower cost. In 1953 water-based fluids began to be utilized as a fracturing fluid, and a number of gelling agent additives such as surfactants were added, to the fracturing fluids, to reduce emulsion with formation fluid. Subsequently, additional clay stabilizing agents were improved and incorporated with water and used as a hydraulic fracturing fluid to fracture many reservoir formations. Alcohol and foam were also used to improve water-based fracturing fluids and utilized to fracture more formations. Currently aqueous fluids such as acid, brines, and water are utilized as base fluids with around 96% of all fracturing treatments using a propping agent. During the early years of the 1970s, the key advance in using fracturing fluids was in applying metal-based cross-linking agents to increase the viscosity of gelled water-based fracturing fluids designed for deeper wells at higher-temperature conditions [1].

The key factor of technological revolution is due to the fast evolution of drilling and completion techniques as well as the improvement of the fracturing technology. From the primary explosion technology of nitroglycerin to the newest fracturing technology of synchrotron, the developed fracturing technology has gradually improved the shale gas recovery efficiency.

The earliest nitroglycerin explosion technology was used in the 1970s in a vertical well with an open-hole completion. This technique affected wellbore stability and caused very limited penetrations. In 1981, a new fracturing fluid combined of nitrogen (N_2) and carbon dioxide (CO_2) foam was utilized in vertical wells in shale gas formations. This implementation led to gas recovery increase by 3–4 times and reduced formation damage. Subsequently, in 1992 the first horizontal well was drilled in shale gas formation in Hammett basin. Horizontal wells then

Stage	Year	Total well number	Fracturing technology
Initial	1979	5	High-energy gas fracturing
	1981	6	N_2 and CO_2 foam fracturing
	1984	17	Cross-linked gel fracturing, liquid quantity 105 gal (378 m3)
	1985	49	Cross-linked gel fracturing, liquid quantity 5 × 105 gal (1892 m3)
	1988	62	Cross-linked gel fracturing
	1991	96	Horizontal well and cross-linked gel fracturing
	1995	200	Horizontal well fracturing and cross-linked gel fracturing
	1997	300	Riverfracing treatment, liquid quantity 5 × 105 gal (1892 m3)
	1999	450	Riverfracing treatment, inclinometer fracture monitor
	2001	750	Riverfracing treatment, microseismic fracture monitor
	2002	1700	Horizontal well fracturing, riverfracing treatment
Development	2003	2600	New well configuration with 719 vertical wells, 85 horizontal wells, and 117 directional wells
	2004	3500	150 wells with horizontal well stage fracturing 2–4 stages
	2005	4500	600 new horizontal wells where drilling time is greatly reduced
	2006	5500	Synchronous fracturing, lower development costs
	2007	7000	Horizontal well fracturing, synchronous fracturing
	2008	9000	Repeated fracturing
Steady	2009	13,000	Maintain capacity, lower costs, enhancing oil recovery

Table 1.
Stimulation development of Barnett shale gas formation [3].

steadily supplanted the practice of vertical wells. A cross-linked gel was applied as a thickening or cross-linking agent during the period from the 1980s to the 1990s. The fracturing technique of horizontal wells can effectively generate fractured networks and increase the hydrocarbon flow area. This method is favorable because it minimizes the cost and increases hydrocarbon recovery. Thus, the development of large-scale hydraulic fracturing using horizontal wells contributed to the economic development of shale gas resources [2].

A major development was made in 1998 in fracturing technology by introducing a water-based liquid fluid instead of gel. This new fracturing fluid has a low sand (proppants) ratio of approximately 90% less than that used in the gelled fracturing. Thus, fracturing fluid associated cost was minimized by more than 50%. This type of fracture fluid can provide better fracturing performance that may increase the recovery efficiency up to 30% [2].

After the year 2000, a new technology called the segmental fracturing technology has been developed and utilized in horizontal wells during shale gas exploitation. This technology has further been developed and improved to include more than 20 segments leading to improvements in both the recovery efficiency and drainage area. Horizontal segmental fracturing technology is broadly used in the United States in the development of shale gas wells over the standard method by 85% [2].

After the year 2005 using both techniques of segmental fracturing technology and microseismic crack monitoring in shale gas development using fracture horizontal wells has significantly enhanced shale gas recovery. A new brand of fracturing technology was subsequently introduced in the year 2006 which is synchronous fracturing technology that has been utilized in the Barnett shale gas basin. **Table 1** summarizes the development of drilling and completion methods and the history of shale gas development in the Barnett basin, United States [3].

2. Main fracturing mechanisms of improving shale gas reservoir production

The mechanism of fracturing stimulation of shale gas reservoirs is not the same as a conventional or sandstone gas reservoir. Shale gas reservoirs, in general, cannot be

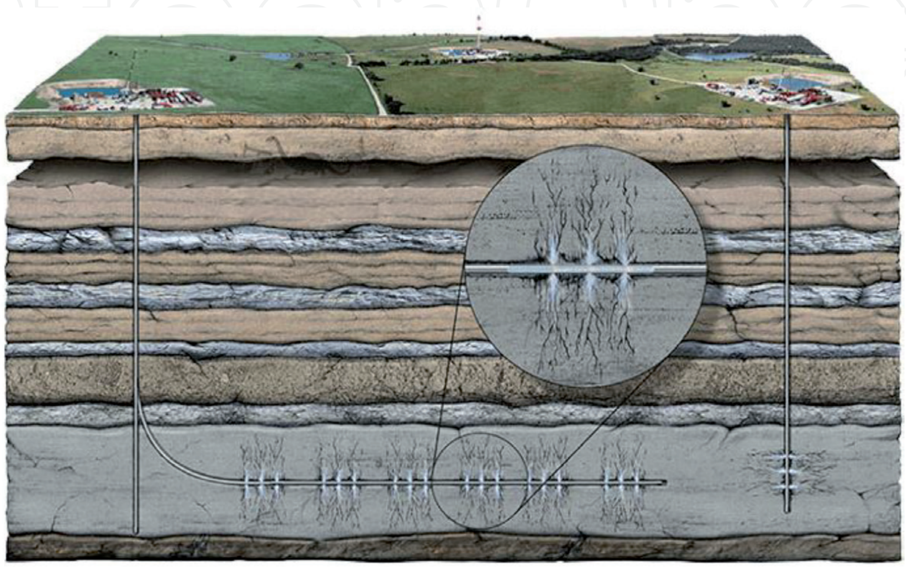

Figure 1.
Sketch map of vertical well and horizontal well fracturing [4].

found as conventional traps, but they are self-generating and self-storage gas reservoirs. The natural fracturing network can particularly enhance shale tight formation permeability [4]. Shale gas capacity can be attained through microfractures in shale formation. These fractures involve both a percolation path and a storage space of shale gas. They create the necessary communication and connectivity for the shale gas to reach the wellbore. Furthermore, shale gas recovery factor can be achieved through the existence of reservoir fractures' and its density and characteristic and

Fracturing technology	Technical physical features	Application area
Stage fracturing	• It is widely used with high technology maturity • Fracturing process conducting with multiple stages	• A horizontal well with multiple production zones and vertical stack tight reservoir
Riverfracing treatment	• Easy preparation of fracturing fluid with low cost • The main element of fracturing fluid is drag-reducing water, to create a denser fracture network, improving permeability • Forcing the gas to flow from the reservoir to the wellbore with greater ease • Less pollution impact on geological formation and limited sand carrying capacity	• Suitable to medium formation depth (1.5–3 km), • Natural fracture system developed reservoir
Hydra-jet fracturing	• Applied to create fractures at different directions and broaden the fracture network to increase hydrocarbon production • It does not require mechanical seal; thus it saves operational time	• Barefoot well completion
Repeated fracturing	• Reinstate the fracture to enhance fluid recovery. • Fracturing multiple wells simultaneously	• Development of new wells • Capacity decline of production well
Simultaneous fracturing	• It is a simultaneous operation process for multiple wells to save operation time • It has a better effect on the reservoir than fracture networks	• For reservoirs with big borehole density and nearby well location
Network fracturing	• Applying high-displacement fracturing fluid during the operation to open natural fracture and create network fractures • Increases formation permeability	• Low formation permeability in which natural fractures are not well developed
CO_2 and N_2 foam fracturing	• Causes less formation damage and pollution • Low filtration and good sand carrying capacity • Good for shale gas desorption	• Water-sensitive reservoir • Shallow reservoir (<1.5 km) and low well pressure
Large hydraulic fracturing	• Utilizes a huge amount of gel • High operation cost for well completion • Causes more damage to the reservoir	• No specific condition for the reservoir; thus it is widely used

Table 2.
Technical characteristics and application of fracturing technologies [7].

opening degree in the reservoir. Shale reservoirs are usually well stimulated and completed with good natural fractures and bedding. High brittleness is one of the significant parameters, which relates to the share failure during shale reservoir hydraulic fracturing process. It is responsible for the formation of complex fracture networks and the connections between natural fractures. Hence, the main purpose of utilizing stimulation technology on shale gas formation is to generate effective fracture networks to improve the reconstruction volume and enhance the reservoir capacity [5].

2.1 Main applied technology of shale reservoir fracturing

Fracturing technology of shale reservoirs can be classified based on the type of well fracturing into three categories, vertical, deviated, and horizontal fracturing wells, as shown in **Figure 1**. Fracturing technology can also be divided based on the type of fracturing fluid used such as gas, foam, gel, etc. Target zone can be fractured into different sections as single section and multi-section fracturing. Moreover, various factors should be taken into account while choosing the choice of fracturing fluid and fracturing technology such as the shale gas reservoir depth, capacity and formation sensitivity, natural fractures, and the well completion technology [6].

The most commonly used fracture technologies now are the multi-section fracturing, riverfracing, hydra-jet fracturing, fracture network fracturing, re-fracturing, and simultaneous fracturing. However, more attention is being given to CO_2 and N_2 fracturing. This fracturing technology's features and application conditions are different as shown in **Table 2**.

3. Multi-fracture network fracturing

Since it was proposed for the first time by Giger in 1985 [8], the concept of horizontal well fracturing has been widely practiced as a valuable technique to improve well production and increase the recovery of unconventional reservoirs. Horizontal well fracturing treatments in field generally create multi-fractures in selected intervals along the wellbore. Processes of fracture initiation and propagation in horizontal wells are different from those in vertical wells due to the larger contact surface area with the formations, thus resembling more complex reservoir situation. When multi-fractures are propagated, they often join or intersect with each other, forming patterns that are known as multi-fracture networks, which immensely increase the storage capacity and the fluid transmissibility of formations. Multi-fracture networks are not easy to be assessed or studied due to the complexity; however, they are evaluated using mathematical and statistical techniques and may be represented using fractals.

3.1 Creation of the multi-fracture network

The classical hydraulic fracturing theory indicates that the main formed fracture is a symmetric bi-wing plane extending parallel to the direction of maximum principal stress. However, field hydraulic fracturing treatment is completely different as complex fracture networks take place where the main fracture and other smaller branch fractures simultaneously extend in the fracture propagation zone [9–11].

Microseismic mapping shows that hydraulic fracturing in shale forms a multi-fracture network system [12–15] which consists of complex fractures as shown in **Figure 2** [16]. It was concluded from the mapping that natural fractures' direction was to the northwest and the propagation of the induced hydraulic fractures direction was to the northeast where they intersected with natural fractures. This led to many crosscutting linear features and formed a complex fracture. Based on fracture extension characteristic in shale reservoirs, hydraulic fractures are classified into four major types [16]: single plane bi-wing fracture, complex multiple

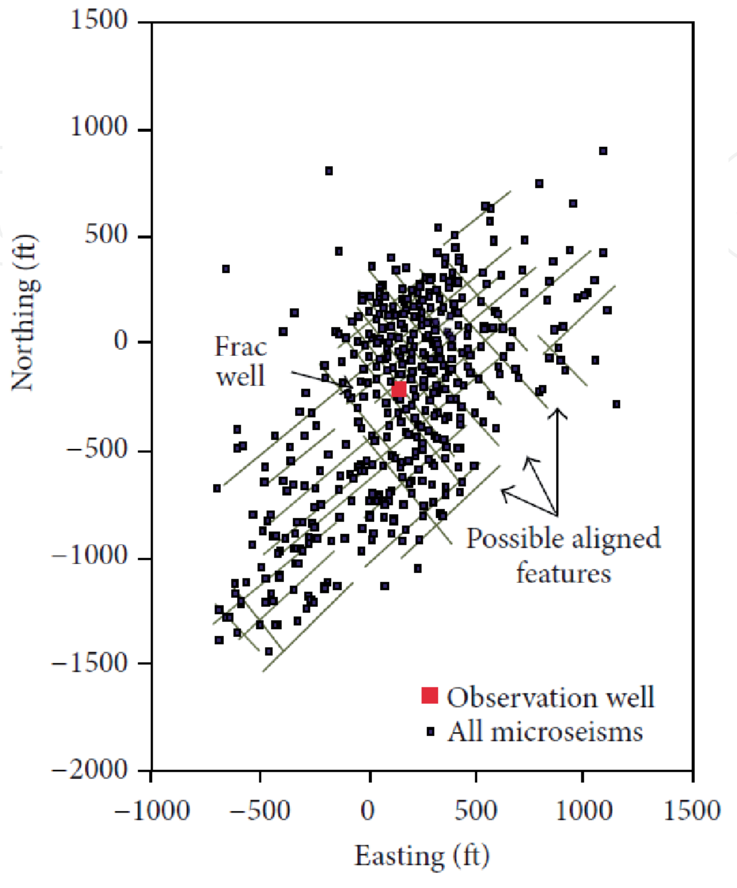

Figure 2.
Multi-fracture network extension in shale reservoirs during hydraulic fracturing (after Warpinski et al. 2008 [16]).

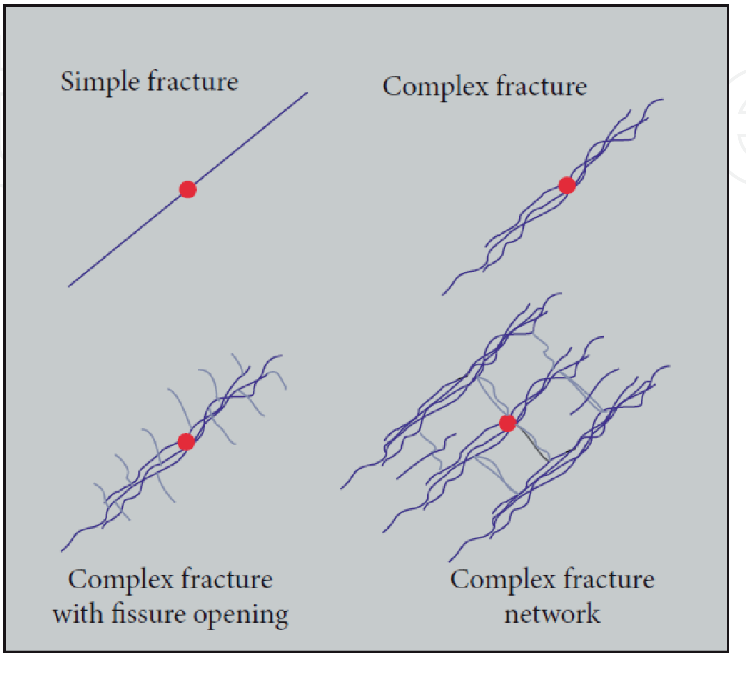

Figure 3.
The hydraulic fracture classification complexity (after Warpinski et al. 2008 [16]).

fracture, complex multiple fracture with open natural fractures, and complex fracture network as shown in **Figure 3**.

Confirming field observation from seismic mapping, simulation experiments [17–22] show that induced hydraulic fracture presents three types of extensions when intersecting with natural fractures: crossing the natural fractures, extending along the natural fractures or crossing, and extending along at the same time. It was concluded that fracture network would highly form during fracturing process of naturally fractured formations [23]. Moreover, several laboratory experiments confirmed that fracture network exists [24, 25] and found that the fracture network would easily form under low fluid viscosity injection [26, 27]. Other observations proposed that multi-fracture networks in shale reservoirs area are key to increase stimulated reservoir volume (SRV) where treatment success relies on whether hydraulic fracture could extend to form multi-fracture network [28–30].

3.2 Factors affecting multi-fracture network fracturing

Understanding fracture initiation and propagation rules are the main issues faced when commencing hydraulic fracturing because several important geological and engineering factors affecting the multi-fracture network formation are to be considered [31].

3.2.1 The geological factors.

1. Mineral composition. Brittleness is controlled by mineralogy as brittleness mineral concentration, the rock brittleness gets higher, and the development of natural fractures becomes better (mineral concentration increase/decrease).

2. Mechanical properties. Poisson's ratio and Young's modulus are combined to reflect the rock ability to fail under stress (Poisson's ratio) and maintain a fracture (Young's modulus) once the rock fractures. The lower Poisson's ratio and higher Young's modulus value, the more brittle the rock, and the fracture extends into fracture network.

3. Distribution of natural fractures. As natural fractures have great effect on hydraulic fracture extension, the more developed the natural fractures are, the more complex is the extension of hydraulic fracture.

4. Horizontal stress field. Multi-fracture network is controlled by intersecting intensity between induced fractures and natural fractures. Hydraulic fracture would propagate along natural fractures under low horizontal stress and cross natural fractures under high horizontal stress conditions.

3.2.2 The engineering factors.

1. Net fracturing pressure. Greater fracturing pressure would cause more complex fractures where it is possible to induce branches of hydraulic fracture to form a complex fracture network.

2. Fluid viscosity. The viscosity has an important influence on the complexity of fracture extension; from the laboratory experiments, it is obvious if the fluid viscosity gets higher; the complexity of fracture is significantly reduced. The injection of high viscosity fluid in field treating will reduce the complexity of fracture network [32–35].

3. Fracturing scale. The impact of fracturing scale can be seen on the production scale, as large amounts of the fracturing fluid volume are pumped; the longer the total length of fracture network, the more complex the resulted fracture network, and the higher the corresponding well production. Using large fracturing scale is an important measure to increase the SRV, which is essential to improve stimulation effect in the shale fracturing, where the bigger the SRV is, the higher the production.

The essential goal for the treatment is to get the most out of each stage and each cluster in the fracturing network. The optimization of fracturing fluid and minding the aforementioned factors can help achieving even flow distribution and network efficiency, both of which can help contribute to increased production. The practices over have realized that, in most cases where it has been measured, only 30–60% of the fractured clusters in a wellbore are providing measurable production [36].

4. Re-fracturing technology

Unconventional reservoirs show significant decline rates after few months of production compromising the economics and imposing the need for increasing or stabilizing production. The decline in production from the unconventional reservoirs is attributed to the closure and damage of the fracture networks within the formations. Hence, re-fracturing as an emerging technology has become a viable option for sustaining production and increasing reserves. Re-fracturing is a preferred option over drilling and completing new horizontal wells as it can be carried at only a fractional cost of up to 25–40% [37], thus minimizing the related financial and safety risks.

Production decline rates from unconventional reservoirs are more rapid than those in conventional reservoirs because of the ultralow permeability, limited reservoir contact, and the original completion strategy. The ability of re-fracturing technology provides a potential to extend the productive life of the unconventional reservoirs beyond the normal and up to an additional 20–30 years [38]. Re-fracturing restores production from underperforming formations by increasing fracturing networks, replacing damaged proppant, bypassing skin zones, and connecting old and new fractures [39]. Successful re-fracturing can increase the estimated ultimate recovery (EUR), shorten the capital return time, and increase the net present value (NPV) of the unconventional reservoirs. Decline curve analysis (DCA) showed that re-fractured wells achieved an average of 60% increase in NPV [40]; therefore, re-fracturing application helps reduce the variability in the unconventional reservoir performance and considered the best option for tackling production declines.

4.1 Re-fracturing process

Re-fracturing literally means a second hydraulic fracturing through same or new perforations to repair or recreate fracture networks within the same formation. If a re-fracturing treatment was carried out after a re-fracturing, then it would be considered a tri-fracturing [41].

Practically, re-fracturing is carried out when the initial hydraulic fracturing treatment was undersized or when suspected skin damage exists [42]. It is possible to use the existing fractures for the re-fracture and still generate a new fracture network sufficient to increase production. In a formation with its low in situ stress anisotropy, pressure can be created within the fracture itself to cause the reservoir to be fractured in new directions. Reusing the existed fractures helps control the cost of re-fracturing. Therefore, another approach for re-fracturing is to add perforations between the existing fractures to create additional fracturing networks as shown in **Figure 4**.

4.2 Re-fracturing methods

There are many ways available to perform re-fracturing; however, three most common re-fracturing methods are selected for consideration, namely, the diversion method, the coiled tubing fracturing method, and the mechanical isolation method [43]:

- Diversion: This method uses diverting agents to plug the existed fractures or perforations, allowing re-fracturing reallocation to new areas. However, it is difficult to control which segment of the lateral would be stimulated that is why it's also known as a "pump and pray method." Yet, this method is the most widely used in the industry likely because it is the most cost-effective.

- Coiled tubing: This method utilizes resettable packers where re-fracturing is targeted. However, at low rates through coiled tubing, this method is considered inadequate for open-hole environments.

- Mechanical isolation: This method typically uses expandable liners and plugs. However, it requires new hardware for re-fracturing which increase costs substantially because it would often need to use a full new liner.

As re-fracturing technology gains popularity in unconventional reservoirs, the ability to isolate reservoir access points and redirect the fracturing fluids and proppant to different parts of the reservoir is crucial to achieving a successful treatment. All known methods have advantages and disadvantages; however, the often selected method is based on their ease of use, cost-effectiveness, and environmental impact.

4.3 Selection for re-fracturing

Many wells are drilled with outdated completion designs; for that, they aren't efficiently producing the reservoir formations. These wells are specifically targeted when engaging re-fracturing because it is an economical practice to mitigate the flow rate decline and maximize reservoir deliverability [44].

The process of choosing which well to re-fracture is known as "candidate selection" [45], and the following are criteria which are often considered [46]:

- Logs or tracers indicating unproductive sections of wellbore

- Initial completion used wrong fracture fluid or proppant type

- Degree of production depletion

- Degradation in fracture conductivity or propped half-length

- Productivity of the reservoir

- Performance of other nearby wells

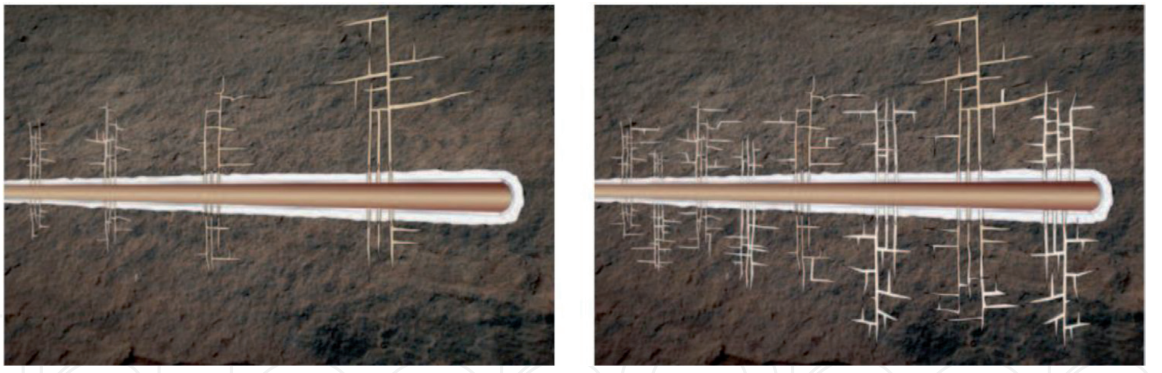

Figure 4.
(left) a hydraulic fracturing stimulation created a fracture network (right) after re-fracturing, and additional complex fracture network has developed (Allison & Parker 2014 [38]).

The selection methodology must be customized to fit the particular needs of a given field where substantial incremental reserves can be added if the correct candidate selection process is followed [47].

4.4 Evaluation of re-fracturing

After re-fracturing, a well may experience increase in production due to new fractures or extension of existing fracture networks. The success of re-fracturing can be determined by empirical parameters such as production rate 30 days before and following re-fracturing, EUR ratio based on DCA [48].

Computer programs can simulate re-fracturing scenarios at a considerable degree of accuracy despite the fact that all predictive methods lack robustness that accounts for the original production depletion and the conditions after re-fracturing. However, as technology advances, well performed computer models are able to generate trustworthy forecasts that allow decision-makers to confidently evaluate the economic success or failure of re-fracturing.

5. Simultaneous fracturing technology

Simultaneous fracturing or multiple fracturing (simul-frac) technology is the hydraulic fracturing technique that fractures multiple wells simultaneously. Simultaneous fracturing applies a shortest well-to-well distance to allow both the proppants and fracturing fluid flow through the porous medium from well to well under high pressure as shown in **Figure 5**. The purpose of the multiple simultaneous process is to increase the recovery efficiency and productivity, of the wells, by increasing the surface area subject to flow through the newly created dense fractures. The typical practice of simultaneous fracturing initiates with two horizontal wells of the same depth; however, currently up to four wells can be simultaneously fractured [46].

Many researchers have performed different field experiments to examine the simultaneous fracture multiple adjacent horizontal wells to create complex fracture networks. Even though field attempts have shown significant improvement with simul-frac instead of stand-along wells [50], microseismic information [51], and numerical simulations [52–58] also demonstrate a complex fracture network made through simul-frac. However, the reasons behind its success are not yet well understood. Multiple hydraulic fracture technique is a complex method that requires considering not only the hydraulic fracturing procedure but also fracture interaction between multiple fractures. The hydraulic fracturing treatment is a

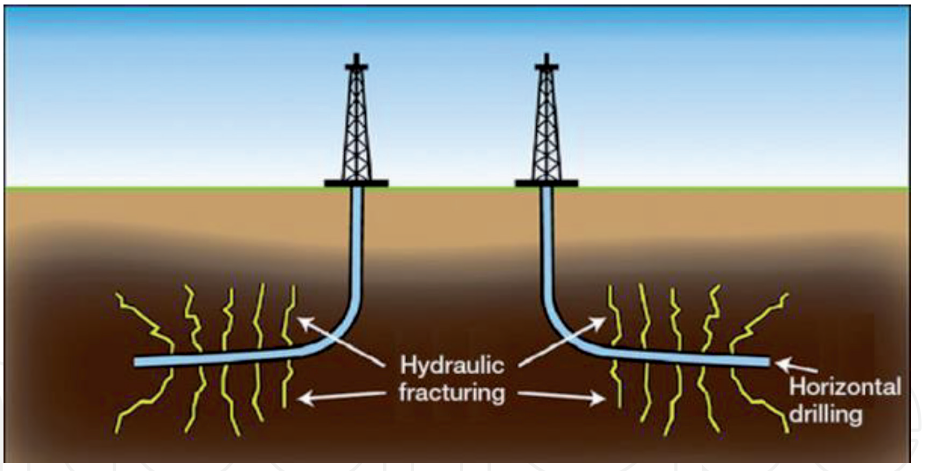

Figure 5.
An example of simultaneous fracturing [49].

typical hydromechanical fracture coupling problem, wherein the following three basic processes involve in [59]:

a. Rock deformation made by fluid pressure applied on fracture surface

b. Fluid flow into the fractures

c. Fracture growth

The fracture interaction between multiple fractures would significantly result in stress shadow effects that can cause stress field and fracture geometry alterations.

With the advance of computer processes, more numerical tools have been developed to become reliable and convenient techniques to investigate the treatment methods of hydraulic fracturing. Moreover, the numerical technique of finite element [60] is a well-established scheme to study rock engineering issues, and also it is frequently used in the last three decades to simulate hydraulic fracture propagation [61]. However, there are many scientific articles published on different finite element methods to numerically study the process of hydraulic fracturing [62–82].

6. Horizontal well staged fracturing technology

Horizontal well fracturing technology is the main technology promptly utilized to low permeability reservoirs. However, in deep shale reservoirs, the use of traditional single stimulation cannot meet the production requirements. Thus, a new technology of horizontal well pressure cracking has been introduced. Zebo et al. [83] found that, based on the process and concerned parameters of horizontal well fracturing, increasing technical problems during reservoir exploration and development, horizontal section becomes popular where sub-fractured horizontal well technique has wide application potentials. Furthermore, the sub-fracturing technology is an important tool in the technology of staged fracturing. Packer as a completion tool does not consist of multicolumn zones, and supporting tools are necessary for safety and to increase the possibility of successful fracturing treatment.

The success of horizontal well fracture is mainly due to the mechanical properties of the rock, stress, shaft stress fracture initiation, and elongation mechanism. Moreover, the horizontal well sub-fracturing should be considered to obtain better fracturing design and to ensure treatment success and efficiency. To achieve the expected outcomes from well completion of a fracturing job, certain issues must be monitored such as the borehole or near wellbore area, permeability anisotropy, blocking natural cracks, and stimulation failure. Up to date, the horizontal well fracturing technique has become one of the preferred tools to solve these problems. Thus, the main applied technology of horizontal well fracturing consists of limited flow fracturing technique and sub-fracturing process. The following section will describe these techniques.

6.1 Limiting entry fracturing

This technique limits the number of perforations and their diameter while injecting a large volume of fracturing fluid that causes increasing the bottom hole pressure on a large scale. Therefore, the fracturing fluid is forced to shunt into limited entries creating new fractures as shown in **Figure 6** [85, 86]. The main advantages of this technique are a relatively simple operation, short operation time, the fact that multi-fractures are created in a single operation which is environmentally favorable for reservoir protection. However, this technique has some limitations including high perforation back pressure, difficult to control any single fracture, and fractures which may not form in perforations of long interval horizontal well.

An example where limited entry fracturing technology was applied in horizontal well is Zhao 57-Ping 35 of Daqing Oil Field [84]. The well was divided into 4 sections each containing 19 perforations, and an isolating packer was set above the kickoff point. Using two simultaneous pumping facilities, a total fracturing fluid volume of 374.3m^3 with an average sand ratio of 35.6% was injected at a rate of 7.5 m^3/min. The fracture initiation pressure was 30.5 MPa, four fractures were created, and the total fracture span was 400 m. The entire operation took 79 minutes. This treatment achieved success allowing the production after fracturing to increase 20–30 times and reach the production level of 4 vertical wells.

6.2 Staged fracturing technique

As limited entry fracturing cannot operate on all the target layers at one time, staged fracturing technique is used when the horizontal section is long and many layers are targeted for fracturing. Staged fracturing creates many fractures by utilizing packers and/or other segmenting materials. Operating a section by section at the time, one fracture is created in every section. The key points to achieve staged fracturing are tools and technique that fulfill the treatment requirements.

There are three types of staged fracturing techniques often used: the bridge plug fracturing, through coiled tubing fracturing with straddle packer and gel

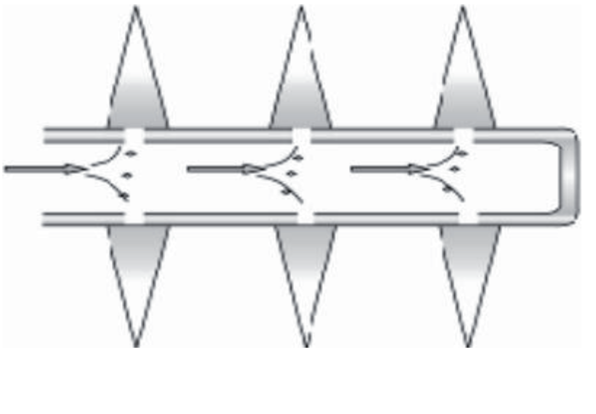

Figure 6.
Technique of the limited entry fracturing of a horizontal well [84].

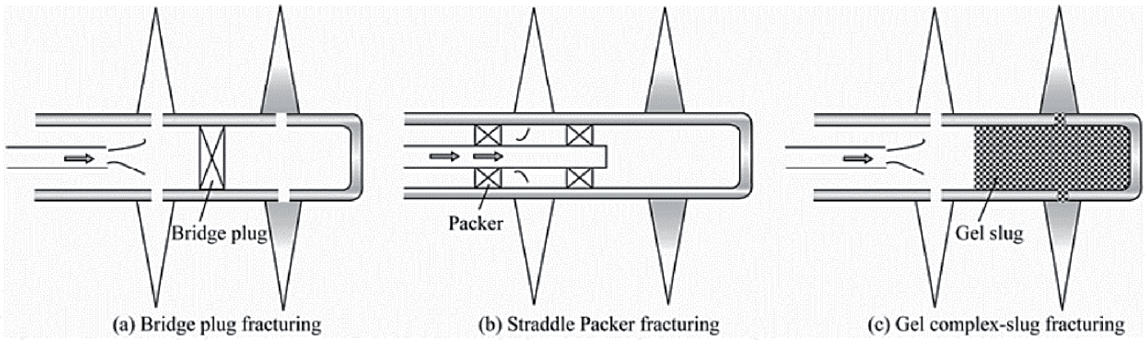

Figure 7.
Staged fracturing mechanism of horizontal wells [84].

complex-slug fracturing as shown in **Figure 7**. Contrary to packer separation, the gel complex-slug fracturing avoids the risk of downhole tool stuck, but in the latter, the fracture initiation points are difficult to control.

An example where gel staged fracturing technology was applied in well Saiping-1 of Changqing Oil Field where four fractures were created. The process is briefly described as the following: perforating the end of horizontal well section, followed by first fracturing treatment, running a production test, and temporary plugging the first section by sand filling gel plug and, next, repeating the process in perforating the second, third, and fourth sections followed by a formation pressure and production tests.

7. Evolution of fracturing fluid and the chemicals

The first hydraulic fracturing treatment was implemented in Hugoton Gas Field in Grand County, state of Kansas, during 1947. By the end of 1952, many fracturing treatments were performed with refined and crude oils. Thus oil-based fluids were the first fracturing fluid utilized for this purpose due to their benefits which are cheap and permitting greater volumes at a lower cost. But due to the safety and environmental issues, which are associated with their applications, it was encouraged that the industry move toward in developing an alternative fluid. At the beginning of 1953, for the first time, water fluid was used as a fracturing fluid; and a number of gelling agents were developed. However, water-based fluids with water-soluble polymers mixed to prepare a viscous solution are commonly used in the fracturing treatment. Since the late 1950s, more than 50% of the fracturing treatments were performed with fluids consisting of guar gums, high-molecular-weight polysaccharides composed of mannose and galactose sugars, or guar derivatives [87].

In 1964, surfactant agents were added to reduce the emulsion formation when in contact with the reservoir fluid; however, potassium chloride was added to decrease the effect on clays and other water-sensitive formation components. Later, additional clay stabilizing agents were developed to enhance the potassium chloride, allowing the use of water in different geological formations. In the early 1970s, a major revolution in fracturing fluids introduced the use of metal-based cross-linking agents to improve the viscosity of gelled water-based fracturing fluids for extreme reservoir condition (i.e., high temperature). Later a critical development was made on gelling agent to achieve a preferred viscosity. Also guar-based polymers are still used in fracturing jobs at reservoir temperatures below 150°C. Other fluid improvements, foams, and the addition of alcohol have enhanced the use of water in more geological reservoir formations. Moreover, various aqueous fluids, such as acid, gas, water, and brines, are currently used as the base fluid in approximately 96% of all fracturing treatments employing a propping agent [87].

As the hydrocarbon drilling and production have moved toward deeper reservoirs with high pressure and temperature condition, more fracturing treatments have been developed to be compatible with these conditions. Therefore, gel stabilizers and thermally stable polymers have been developed in which gel stabilizers can be utilized with around 5% methanol, but synthetic polymers have shown a sufficient viscosity at temperatures up to 230°C [88]. After that, chemical stabilizers have been developed and possibly used with or without a methanol. The improvements, which are made in cross-linkers and gelling agents, have led to systems that can permit the fluid to reach the well bottomhole in high-temperature condition before cross-linking, therefore, reducing the effects of high shear in the production tubing. Recently, nanotechnology has been introduced in the design of new, efficient hydraulic fracturing fluids [88]. For example, nanolatex silica is used to reduce the concentration of boron found in conventional cross-linkers. Recent advancement in nanotechnology is the use of small-sized silica particles [20 nm] suspended in guar gels to improve fracturing treatment [89]. Therefore, the following section will discuss the use of CO_2 and N_2 as fracturing fluid to enhance the hydrocarbon fluid production and to store CO_2 into the geological formation to minimize the greenhouse emission. Also it will provide a brief information on hydra-jet fracturing.

7.1 Fracturing using CO_2 and N_2

In the ordinary fracturing, large amounts of freshwater, sand, and chemicals are injected into the ground at high pressure. It has been reported that up to 9.6 million gallons of water on average are used for a single well fracturing; this lead to the use of more than 28 times the water for wells before fracturing, putting farming, and drinking sources at risk in arid regions, especially during drought [90]. Some of the water used for fracking is brought back to the surface and recycled, but the most of it is lost deep into the formations. Thus, fracking can increase demand for water by up to 30 percent, and this can be a major increase for groundwater consumption.

To solve the water scarcity problem, the fracturing using water, carbon dioxide, and nitrogen is commonly referred to the process in where substantial quantities of both nitrogen and carbon dioxide are incorporated into the fracturing fluid. Amounts of nitrogen and carbon dioxide are incorporated separately into an aqueous-based fracturing fluid to provide a volume ratio of nitrogen to carbon dioxide within an estimated range between 0.2 and 1.0 at wellhead conditions. The volume ratio for the total of both carbon dioxide and nitrogen to the aqueous phase of the aqueous fracturing fluid ranges between 1 and 4. The aqueous fracturing fluid that contains the nitrogen and carbon dioxide is injected in the well under conditions in which the pressure required is high enough to implement hydraulic fracturing of the subterranean formation undergoing treatment. In order to provide a viscous aqueous-based fracturing fluid, a thickening agent may be added into water. Additionally, a propping agent is to be incorporated into a portion of the fracturing fluid. Only then can carbon dioxide and nitrogen be added to the fluid. Carbon dioxide is incorporated in its liquid phase and the nitrogen in its gaseous phase. The use of carbon dioxide and nitrogen as fracturing fluids is discussed briefly in this essay.

Currently, carbon dioxide fracturing is one of the most effective and cleanest approaches available in order to increase oil and gas production. To produce the viscous aqueous-based fracturing fluid, carbon dioxide is injected in its liquid state using conventional frac pumps. Injection rates for it can be improved by incorporating booster capacity. An upside of using carbon dioxide in this process is that it can carry high concentrations of proppant in foam form due to its density and is compatible with all treating fluids (including acids). Because of that density, it is also not susceptible to gravity separation. Additionally, carbon dioxide can be pumped with synthetic and natural polymers, lease crude, or diesel as a foam or microemulsion, increasing the hydrostatic head to or greater than that of fresh water and decreasing the viscosity of the system. This feature of carbon dioxide results in vastly reducing horsepower costs and a decrease in the applied treating pressures. Another benefit of carbon dioxide is that it dissolves in water which causes it to form carbonic acid that dissolves the matrix in carbonate rocks. It buffers water-based systems to a pH of 3.2 which can also control clay swelling and iron and aluminum hydroxide precipitation. Known to act as a surfactant to significantly reduce interfacial tension and resultant capillary forces, carbon dioxide thus removes fracturing fluid, connate water, and emulsion blocks. In regard to it being one of the cleanest approaches in increasing gas and oil productions, carbon dioxide provides the energy to remove formations fines, crushed proppant, reaction products, and mud that is lost during drilling. In addition to that, swabbing of treating fluids can be greatly reduced which will allow for saving in associated treatment costs. Lastly, unlike other agents a carbon dioxide treatment with a 70 quality foam job allows low amounts of the water to contact the formation, roughly 30 percent compared to a gelled water fracturing. This decrease chances of clay swelling and inhibited production. All these benefits of using carbon dioxide as a fracturing fluid in wells with low bottomhole pressure or sensitivity to certain fluids make it a strong alternative candidate.

Although containing different properties, nitrogen similar to carbon dioxide comes with many benefits for fracturing fluids. Nitrogen for the fracturing fluids can be supplied by air products and provides both performance and cost advantages over certain formations of water-based fluids. Although water-based fracturing fluids are commonly used for hydraulic fracturing due to their advanced proppant transport into the fracture, they do also come with disadvantages. Because they can cause water saturation around the fracture and clay swelling which can result in hindering the mass transport of hydrocarbons from the fracture to the wellbore, water-based fluids are often unsuitable for water-sensitive formations. Nitrogen fracking fluids are an excellent alternative to water-based fluids in water-sensitive formations, depleted reservoirs, and shallow formations as they do not result in any water saturation.

Four main types of nitrogen fracturing fluids are used commercially: pure gas, foam, energized, and ultrahigh quality (mists). Foam fracturing fluids typically consist of a water-based system and a gas phase of nitrogen volume in the range of 53 to 95%. Below 53% nitrogen, the fracturing fluid is considered energized. Above 95 percent nitrogen, the fracturing fluid is considered a mist. Cryogenic liquid nitrogen fracking fluid is considered to be the fifth type of nitrogen fracturing fluids used. However, it is rarely employed for commercial operations due to material restrictions and equipment requirements.

7.2 Hydra-jet fracturing

The process of hydra-jet fracturing combines hydra-jetting with hydraulic fracturing and involves running a specialized jetting tool on conventional or coiled tubing. Dynamic fluid energy jets form tunnels in the reservoir rock at precise locations to initiate the hydraulic fracture which is then extended from that point outwards. By repeating the process, one can create multiple hydraulic fractures along the horizontal wellbore [91–93]. The idea of hydra-jet fracturing is not a new one.

In fact, it was used a century ago with low-pressure jets [94] where waterjets with erosive materials were used to cut rock and glass. Because erosion does not involve a backflow hindering the sand cutting process, cutting steel plates, wellheads during the Iraqi war, and rock quarries tend to be easily be done. Hydra-jet cutting may be mistakenly claimed as a result of a perforating process which can be seen when used on the rocks sandstone and limestone.

For these two rocks, assume that the jet is used to perforate formation rock. Also assume that the jetting process creates a perforation with a larger inside diameter than the jet nozzle. The velocity of the fluid flowing into the perforation tunnel would be incredibly elevated. Near the bottom of the perforation, the velocity of the flowing fluid would dramatically decrease. If the flow area is sustained and there is no presence of friction, the fluid pressure will be equal to the original jet pressure per the example. However, this tends to be an unlikely happening because pressure losses are typically high. To further explain this, jet boundary friction works to convert kinetic energy to heat loss causing jet flaring. This drastically reduces jet velocity, which in turn reduces the pressure per unit area of impact. This results in a low-pressure transformation efficiency. More importantly, rocks can still be fractured when enough pressure is applied to the jets even at this low of a pressure efficiency rate. An important note is that laboratory tests have shown that rock fracturing is commonplace when jet pressures are high. However, when high-pressure and low-energy transformation efficiencies are used hand in hand, they are technically and economically impractical.

8. Summary

The desired objective of fracturing is to develop and effectively produce from a shale reservoir. To ensure a successful fracturing treatment, a proper fracturing technology must be utilized based on the reservoir characteristics as the reservoir mineral content, physical properties, and geological condition. The utilized formation fracturing technique has a different desired environment to achieve the maximal recovery. During the process of fracturing treatment, the content of a fracturing fluid should be checked based on the formation mineral content and physical properties to improve reservoir permeability and reduce formation damage.

The forming of multi-fracture network is the key to obtain an effective hydraulic fracturing treatment in shale reservoirs. If higher treating net pressure is achieved, lower fluid viscosity is used, and larger fracturing scale attempt would be more helpful to form a fully fracture network. The reservoir geological factors also have high attributes, where brittleness index, elastic characteristic of rock mechanical properties, horizontal stress, and existence of natural fractures are useful to obtain better results of fractures developing into multi-fracture network.

Re-fracturing has the potential to re-energize natural fractures and extend and replace low conductivity existing fracture network. Utilizing re-fracture treatment successfully depends on technology that allows access to larger volumes of unconventional reservoirs. Monitoring the effectiveness of well completions helps guide technologies and methods to gain control of the wellbore to maximize EUR and NPV. Re-fracturing treatments have significant impact on production, and economics of unconventional reservoir development and consideration should be taken to determine the best way to achieve successful re-fracturing as production starts to decline.

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