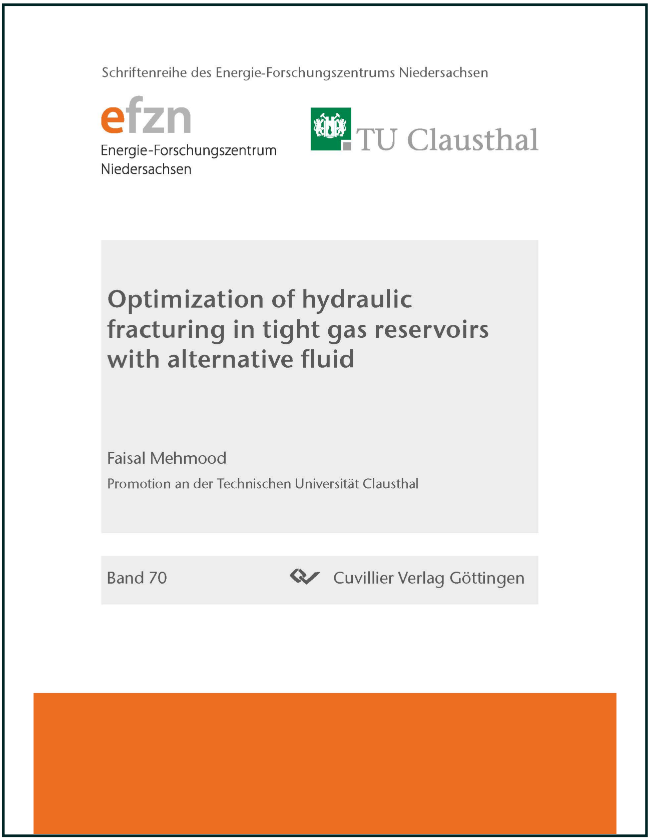
Faisal Mehmood (Autor)

Optimization of hydraulic fracturing in tight gas reservoirs with alternative fluid



https://cuvillier.de/de/shop/publications/8494

1 Introduction

1.1 Motivation and objectives

Petroleum is going to play a major role in the worldwide energy mix for the years to come with the coexistence of alternative energy such as renewable in industrial, residential, commercial, transport sectors etc. As the production of petroleum from conventional resources is declining, the unconventional resources are going to play an important role to meet the energy demands. The inclusion of unconventional resources will also extend the hydrocarbon industry life by many decades and increase the production to meet the increasing energy demands. Conventional reservoirs are characterized by high porosity and permeability rocks having accumulations of hydrocarbons which migrate from source rock and are stored due to structural or stratigraphic traps. Whereas, unconventional reservoirs accumulate over large area having low/ultra-low porosity and permeability, therefore, commercial production without stimulation is not possible. Unconventional reservoirs can also be defined as reservoirs which need change in permeability-viscosity ratio to provide commercial production. The development of unconventional resources on commercial scale especially unconventional hydrocarbon revolution in North America has resulted in increasing the recoverable reserves of petroleum (Cander, 2012; Leimkuhler and Leveille, 2012; C. Zou et al., 2013; Zou et al., 2014; C. N. Zou et al., 2013).

The conventional oil and gas production for more than one century including estimated 1732×10^{8} t oil and 79×10^{12} m^3 gas has led to the industrial development. Due to lower recoveries, substantial resources enough to supply energy for a long period of time, remain underground. While, unconventional oil resources are considered equivalent to conventional resources, the unconventional gas resources are vastly abundant compared to conventional gas resources (Jia, 2017). The high-quality resource of conventional reservoirs, easy to extract, is limited. Whereas around 80% of total resources are unconventional and can be characterized as tight oil, tight gas, coal-bed methane, shale gas, shale oil gas hydrates etc. (Holditch, 2006; C. Zou et al., 2013).

Tight gas reservoirs are unconventional reservoirs which mainly produce dry natural gas. Due to lower permeability of equal to or less than 0.1 mD ($<1*10^{-4}$ μm^2) and less than 10% matrix porosity, well stimulation techniques are applied to enhance production. However, the production remains considerably low compared to conventional reservoirs. Therefore, the need for more wells, less well spacing compared to conventional reservoirs arises. In addition to tight sandstones, significant production is also taken from shales, carbonates, and coal-bed methane (Bahadori, 2014; Caineng et al., 2015; Dai et al., 2012; Guo and Gou, 2015; Holditch, 2006; Prud'homme, 2013).

Natural gas is a cleaner fossil fuel compared to oil and coal with fewer emissions and pollutants due to lower CO_2-to-energy-content ratio. It produces only 117 lbs CO_2 per million British thermal units (Btu) in comparison with 161 lb CO_2 per million Btu and 205 lb CO_2 per million Btu for diesel and coal (bituminous), respectively (US EIA). Natural gas is not as clean as renewable energy but can serve as a bridging technology for transition to renewable energy. According to global energy review 2019 (IEA, 2019), the decline in power sector related CO_2 emissions can be attributed to shifting to natural gas from coal in addition to increased renewable energy resources and higher nuclear power output. Natural gas as a bridge fuel can provide with climate benefits in comparison with coal-based energy systems however it is important to minimize its leakage rate (Zhang et al., 2016). Mena-Carrasco et al., (2012) estimated the reduction in air pollution and resulting health benefits due to natural gas usage in transport and heating. The public concern over environmental issues will also increase its role in the energy mix (Economides and Martin, 2007). Reducing the greenhouse gas (GHG) emissions and improving air quality through efficient extraction and evolution of natural gas system can help in achieving transition towards renewable energy systems. Therefore, utilizing natural gas in an environmentally responsible manner can become pathway to a sustainable energy future (Mac Kinnon et al., 2017). Thus, the role of natural gas in energy transition is of critical importance considering global climate challenges and carbon neutrality goals (Rogelj et al., 2016).

Most of the world's energy demand is met through petroleum resources or fossil fuel in a broader sense. Natural gas production and consumption from conventional and unconventional reservoirs has been on the rise due to its application in different sectors such as industry, residential, commercial etc. Figure 1.1 explains the natural gas share in the global energy mix for 2010, 2015 and 2019, respectively. An increase in the natural gas share to 23% with rising energy demand along with renewable energy at 10% with a subsequent decrease in the coal share can be observed from 2010-2019 (IEA, 2020).

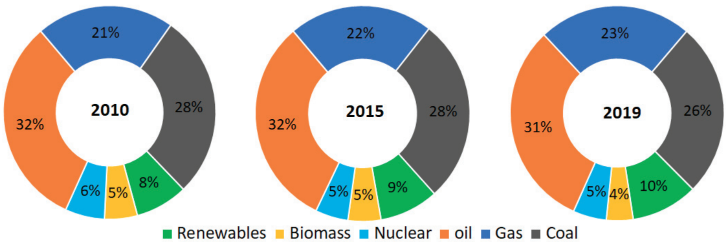


Figure 1.1: share of different energy sources in primary energy demand (IEA, 2020).

In the year 2019, the natural gas consumption increased by 78 billion m^3 (bcm), owing to increased demands of 27 bcm from US and 24 bcm from China, whereas gas production increased by 132 bcm (BP, 2020). The increase in worldwide natural gas consumption from 1970-2019, during which the gas demand grew from around 1 trillion m^3 (tcm) to about 4 tcm, can be observed from Figure 1.2. The highest gas consumption was recorded for North America, Asia Pacific, CIS (Commonwealth of Independent States), Middle East, Europe, South and Central America and Africa, respectively.

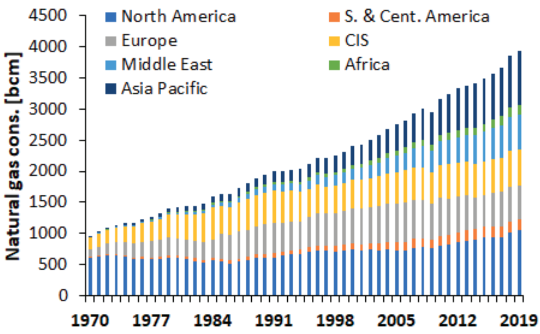


Figure 1.2: increase in gas consumption for different regions since 1970 (BP, 2020).

The trends of oil and gas production since 1970 can be observed from Figure 1.3. In 1986, the natural gas production of CIS region increased from North America. Whereas, due to unconventional hydrocarbon production especially in early 2000's, North America became highest producer of natural gas. Highest gas producer regions can be listed in the following order as North America, CIS, Middle East, Asia Pacific, Africa, Europe and South and Central America, respectively.

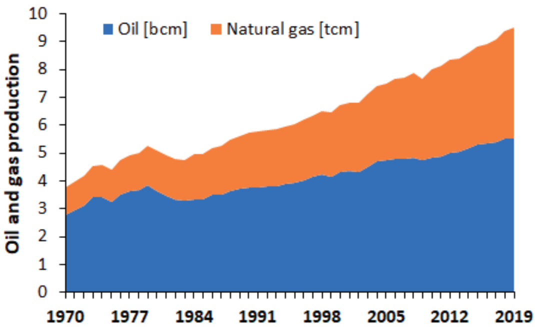


Figure 1.3: increase in global oil and gas production since 1970 (BP, 2020).

The world energy consumption increased by more than 3 times in the last fifty years growing from 192.86 exajoules to 583.9 exajoules (BP, 2020). It is expected that the peak global gas production will remain from 3.7 to 6.1 trillion m^3 (tcm) per year between 2019 and 2060 (Wang and Bentley, 2020; Zou et al., 2016). According to international energy outlook, an increase of more than 40% in global gas consumption is expected between 2018 and 2050 (US EIA, 2019). The global proved gas reserves amount to around 200 trillion m^3. The distribution of proven reserves in different regions is presented in Figure 1.4.

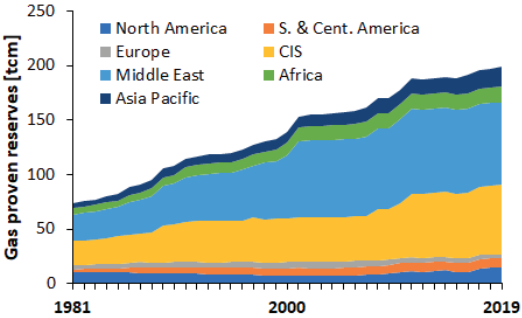


Figure 1.4: proven natural gas reserves of the world (BP, 2020).

Continued development of new technologies and methodologies has resulted in better development of unconventional reservoirs, leading to efficient and expeditious production of petroleum resources. The increased petroleum production is attributed to advanced technologies of horizontal well drilling and hydraulic fracturing in tight and ultra-tight reservoirs. Hydraulic fracturing has resulted in producing 50% of the natural gas and accounts for 33% of petroleum production in the US. Horizontal drilling and multi-stage hydraulic fracturing with optimized well spacing is the solution to enhance petroleum production (Alexander et al., 2011; Economides, 2007; Howarth et al., 2011; Hughes, 2013; Li and Zhang, 2019; Liu et al., 2018; Montgomery and Smith, 2010; Prud'homme, 2013; Rahm, 2011). According to Hughes (Hughes, 2013), around 61% of the wells in US are horizontal which in 2004 were less than 10%. Horizontal and vertical wellbores with hydraulic fracture are presented in Figure 1.5.

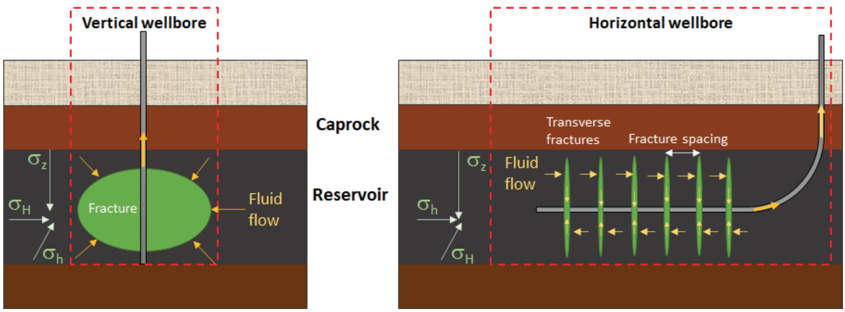


Figure 1.5: vertical and horizontal boreholes with vertical transverse fractures.

Well stimulation can be divided into two basic categories of acidizing and hydraulic fracturing. Due to surface handling issues, health and safety concerns and applicability to specific formation types such as carbonates, acidizing has limited applicability. Hydraulic fracturing on the other hand, as discussed earlier has been widely and extensively applied. In hydraulic fracturing, the injection of fluid into the formation is done at a higher rate compared to the rate at which fluid escapes into the formation i.e., leakoff. Perforce, the pressure rises and when it reaches the limit of formation break down pressure, fracture is initiated normal to the minimum horizontal stress due to tensile failure. With continued injection at a rate higher than leakoff, the fracture propagates further towards a path of least resistance. However, as fracture grows, the leakoff increases due to exposure of more area for injected fluid to escape. In vertical wells, generally a fracture is created along the wellbore axis perpendicular to the least in-situ stress which is normally the minimum horizontal stress. But for horizontal fractures, the geometry is more complicated. Normally, a horizontal well is drilled in the minimum horizontal stress direction so that transverse fractures can be created with optimized spacing. If well trajectory follows maximum in-situ horizontal stress direction, then longitudinal fractures are created (Economides, 2007; Economides et al., 1994; Economides and Nolte, 2000; Guo et al., 2007).

The actual practice of hydraulic fracturing is only a small part of the overall process of drilling, completing, and producing an oil and gas well. Hydraulic fracturing resulting in highly conductive flow paths has been in business since late 1940s. The designing of hydraulic fracture job requires prior knowledge of reservoir and surrounding formation including pressure, stress state, physical properties such as permeability, porosity, mechanical properties such as elastic modulus, bulk modulus, shear modulus, Poisson's ratio etc. The injection of fracturing fluid containing chemicals and proppants is carried out through high pressure rating equipment on the well site. The fluid flows through the production well to the target formation. The pressure of the fluid is increased until the formation breaks down. The break down pressure and closure stress are found before the main fracturing operation through mini-frac tests and fall-off tests. Fracturing can be divided into two stages i.e., pad stage and slurry stage. During the pad stage, fracturing fluid is injected to create the fracture, whereas proppant carrying slurry is injected during the slurry stage. Proppants are injected in order to keep the fracture open under the effect of closure stress after the pumping is stopped. As the closure takes place due to fluid leakoff to surrounding formations, the width of the fracture decreases, and proppants come in contact with the walls of the fracture. These artificially created highly conductive flow paths kept open with proppants (support agents) are essential especially for commercial production from low permeability reservoirs, which were previously abandoned due to poor production. The post fracture testing and performance determines the fracture conductivity and resulting effect on well deliverability based upon the created fracture geometry (Clark, 1949; Economides and Nolte, 2000; Fisher and Warpinski, 2012; Koplos et al., 2014; Montgomery and Smith, 2010; Pang et al., 2016; Prud'homme, 2013).

Hydraulic fracturing is generally performed with water-based fluids. Although it has resulted in increased energy production, the use of water-based frac-fluid have caused problems. Lower support of upper part of fracture in tight/ultra-tight reservoirs, phase trapping especially in sub-irreducible water saturation formations, swelling in water sensitive clays and poor fracture cleanup have resulted in inefficient fracturing operation. In addition, due to the large injection volume requirements, the water availability especially in areas of water scarcity and wastewater disposal have become critical issues. Due to environmental issues, there have been serious concerns of the public over fracking.

Fracturing operations are not conducted in Germany at industrial levels due to such environmental issues. The sandstones of upper Rotliegend, characterized by lower permeability in a high pressure and temperature environment, are the main source of gas production in Germany. The upper Rotliegend consists of series of sandstones, siltstones and shale formations. Due to the depositional environment, permeability anisotropy of 1/10 can be present within the sandstone formations. Thus, through hydraulic fracturing, not only vertical flow barriers within formations were bridged but also horizontal connectivity of the layers were improved. Massive hydraulic fracturing operations were performed such as in Soehlingen Z4 in the year 1982 with 2,582 m^3 frac-fluid and 546,000 kg proppants. Then the technology of multi-stage hydraulic fracturing in horizontal well was successfully applied to Soehlingen Z10 in 1994 (Koehler, 2005). Later, in 2005, horizontal well with multiple transverse fracture was drilled in Leer, where it was found that one of the fractures was not contributing to production due to no support for the upper half of fracture as the proppants fell to the bottom because of delayed fracture closure (Li, 2018). However, due to the large number of fracking operations and associated risks, questions were raised on the safety and environmental stability of fracking technology especially on the storage, transport and disposal of wastewater in Germany (Borschardt, 2012; Olsson et al., 2013). Later, fracking was prohibited for commercial projects especially in consideration of water protection and conservation regulations through environmental impact assessment (Bundesgesetzblatt, 2016; Die Bundesregierung, 2017).

Therefore, alternative frac-fluids need to be analyzed as a solution to the environmental concerns by minimizing the water usage and addressing the associated technical problems. In this work, numerical modeling has been utilized to investigate the applicability and effectiveness of alternative frac-fluid technology in tight gas reservoir case studies from Canada and Germany. Moreover, as the fracture permeability is dependent upon properties of proppant, especially its shape. The effect of changing the proppant shape from conventionally used spherical to rod-shaped on fracture conductivity and long-term performance need to be studied.

1.2 Thesis outline

To minimize the technical and environmental issues of conventional water-based fluid fracking, light alkanes (n-heptane to n-decane) as alternative frac-fluid are proposed. The development, verification, and application of multiphase multicomponent (MM) numerical model for simulation with alternative frac-fluid based upon popular THM framework FLAC3D^{plus}-TMVOCMP is presented. In addition, the implementation of post fracture performance model in FLAC3D^{plus}-TMVOCMP for conventional i.e., spherical and unconventional i.e., rod-shaped proppants under the influence of stress state and mechanical properties contrast between proppant and formation is also presented. The following contents are part of this research work.

Chapter 2 explains why there is a need for alternative frac-fluid. It discusses the major environmental and technical issues associated with conventional water-based fluids utilized in the petroleum industry. In the environmental problems section, issues such as water availability, quality degradation due to chemical additives with details about some major components of frac-fluid and induced seismicity due to wastewater disposal in deep injection wells are discussed. Then the technical problems such as delayed fracture closure, clay swelling, fluid phase trapping, lower frac-fluid flowback are discussed for water-based fluid. Due to the environmental problems, the issue of public disapproval of hydraulic fracturing operation has emerged leading to ban in many countries. Later, alternative fluids for fracturing such as oil-based, gas-based, foam-based are reviewed highlighting their advantages and disadvantages.

Chapter 3 presents the proposed alternative water-less frac-fluid consisting of light alkanes from n-pentane to n-decane. The thermodynamic properties and the PVT behavior of proposed fluid are discussed. Then simulation in a fictive model is carried out to observe the phase change of the fluid under appropriate conditions. A brief introduction about the multiphase multicomponent (MM) fluid flow simulator TMVOC is also included. The phase behavior in terms of appearance and disappearance of light alkanes in liquid and gas phase is discussed.

Chapter 4 is related to the development and implementation of numerical model for MM thermo-hydro-mechanically coupled stimulation with proposed fluid. After a brief introduction of the coupling concept, hydraulic fracturing mechanics is discussed in light of fracture initiation, propagation, orientation etc. Then the numerical model is discussed which is divided into several sections explaining the mass and energy balance, space and time discretization, fracture propagation mechanism, fluid flow in fracture and formation, fluid viscosity calculation etc.

Chapter 5 is based upon the verification of developed model with literature and application to LPG-based frac-fluid stimulation case study of McCully tight gas field, New Brunswick, Canada. The verification is performed to examine the ability of developed model to simulate fracture initiation and propagation and MM fluid flow in isothermal and non-isothermal conditions. Then the application to a case study of McCully tight gas reservoir is explored. In this section, analysis for the hydraulic fracturing performance of propane (LPG)-based, water-based and n-heptane-based fluid are performed. The proppant settling behavior, flowback and production performance for different frac-fluids is also presented.

Chapter 6 covers the stimulation tests for optimization of wellbore yx1 with proposed fluid. Firstly, the model is verified through pressure history match with previously conducted frac-job data. Then the effect of most fluid important parameters such as fluid viscosity, injection rate, injection time is analyzed. Based upon numerous simulations and sensitivity analysis, hydraulic fracturing designs with alternative fluid are proposed and compared with previous fracture jobs.

Chapter 7 introduces rod-shaped proppants as an alternative to spherical proppants for improved fracture conductivity. After a brief literature review, numerical modelling for a production model is discussed incorporating different proppants. Then the influence of different factors such as effective stress, formation and proppant properties, proppant size in a generic model is discussed. Finally, the developed model is applied to wellbore yx1 well for production optimization using different aspect ratio rod-shaped proppants in different design proposals.

2 Need for alternative frac-fluid

Hundreds of thousands of fracturing operations have been performed with water as main fracturing base-fluid. Since 1949, nearly 2.5 million fracking operations have been performed leading to not only increasing the well productivity but also increasing the recoverable reserves. Whereas, until 2010 one million wells were stimulated with fracturing in the US only. A large number of fracturing jobs are also attributed to horizontal well drilling, where a number of frac-stages are performed or to multilateral wells where a number of wells are drilled from a single platform (Gallegos et al., 2015; Kondash and Vengosh, 2015; Montgomery and Smith, 2010; Rubinstein and Mahani, 2015; Gallegos and Varela, 2015). Apart from advantages, several environmental and technical disadvantages are associated with conventional frac-fluid fracking. These issues will be discussed in next sections.

2.1 Environmental problems

The main functions of frac-fluid include initiation and elongation of fracture, proppant transport through mixing tanks and surface pumping equipment to the fracture and placing them in desired location in the fracture (Economides, 2007). Most of the hydraulic fracturing treatment is performed with water-based fluids. The hydraulic fracturing water cycle can be observed from Figure 2.1.

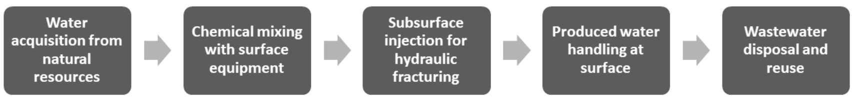


Figure 2.1: water cycle (US EPA, 2016).

During the water cycle for hydraulic fracturing acute environmental issues such as water availability issues especially in areas of water scarcity and declining water table, surface and ground water quality degradation due to wastewater disposal, induced seismicity due to injection of wastewater into deep disposal wells are caused (Jacobs, 2014; Kondash and Vengosh, 2015; Rahm, 2011; US EPA, 2016).

2.1.1 Water availability

The use of water for tapping the unconventional resources utilizing hydraulic fracturing is higher than conventional resources (Zhang and Yang, 2015). In horizontal wells in the US, average annual volumes per well between 15,275 m^3 and 19,425 m^3 water are utilized (Gallegos et al., 2015; Rahm, 2011). According to a study from 2012 to 2014, 116 billion litres annually for shale gas and 66 billion litres annually for unconventional oil were used for fracking in the US alone (Kondash and Vengosh, 2015). The transition from conventional to unconventional resource exploitation leading to high hydraulic fracturing density has increased the water usage per well up to 770% (Kondash et al., 2018).

Due to large water usage for hydraulic fracturing, the public water resources and aquatic ecology are affected. The availability of water for population, agriculture and climate can be seriously impacted especially in areas where susceptibility to droughts is high (Gallegos et al., 2015; Howarth et al., 2011; Jacobs, 2014; Vengosh et al., 2014). It has been reported that huge volumes of water extraction in some regions have resulted in significant depletion of consumptive water resources. Therefore, it is imperative to reduce strain on the water resources (Kondash et al., 2018). In addition, the water use intensity is less compared to other energy extraction methods. The water consumption on per well and total field basis, in major unconventional gas plays in the US can be observed from Figure 2.2.

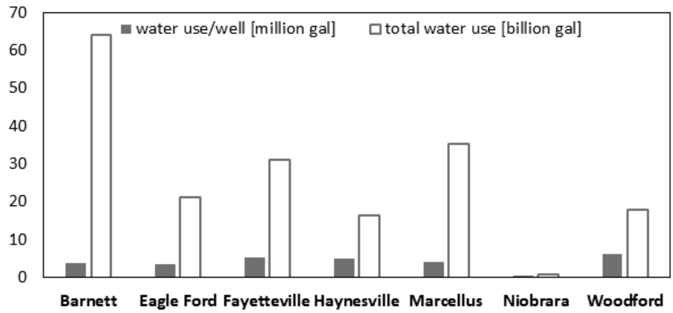


Figure 2.2: water consumption statistics for major unconventional gas plays in US (Kondash and Vengosh, 2015; US EPA, 2015).

2.1.2 Water quality

The contamination of drinking water table by chemicals added to frac-fluids due to spills or leakages, disposal of improperly treated wastewater etc. has been a growing concern. The water-based frac-fluid comprises of toxic and non-toxic components (Elliott et al., 2017). Numerous health problems are associated with these chemicals due to their toxicity. The wastewater management varies in different regions such as evaporation of wastewater and disposal of solid particles as dry waste, processing in wastewater treatment plants or reinjection into disposal wells. The waste fluid from flowback can also cause contamination through leakage or spills, direct discharge without treatment or insufficient treatment. The reinjection at shallow depths can contaminate the fresh water. One solution can be to reuse the wastewater for subsequent fracturing operation, but the scale forming components can block the fractures (Gallegos et al., 2015; Kargbo et al., 2010; Vengosh et al., 2014). Only 4% and 14% of the total volume injected for fracturing operation was reused fracturing wastewater in Marcellus shale (Susquehanna River Basin) and Barnett shale, respectively (US EPA, 2016). In addition, the wastewater volume due to flowback and produced water have increased up to startling 550% from 2011-2016 (Kondash et al., 2018).