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# TECHNICAL AND ENVIRONMENTAL ISSUES IN THE PRODUCTION OF UNCONVENTIONAL SHALE GAS RESOURCES

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**Abstract**

The current global upsurge in the development of unconventional shale gas and tight oil starting from the United States is resulting in increased economic benefits, including significant rise in job creation, lower energy costs and improved security, new sources of government revenue, and improved energy security. Also, there is a substantial decrease in greenhouse gas (GHG) emissions due to the development of this unconventional natural gas resource. Increasing technological advances in directional drilling, hydraulic fracturing and fracturing fluids have led to increases in unconventional shale gas development, raising questions about health impacts. This paper gives a brief review of the physics and thermodynamics of gas flow in such a low porosity and low to ultra-low permeability reservoirs. It also looks at effects of such phenomena a gas desorption/desorption process, non-Darcy flow, gas slippage (Klinkenberg effect), rock deformation caused by change in effective stress in ultra-low permeability reservoirs, hydraulic fracturing and environmental impact of flowback and produced fluids.

***Keywords***: *Unconventional reservoirs; shale gas; shale reservoir parameters, hydraulic fracturing; fracturing fluids.*

## 1. Introduction

Unconventional reservoirs such as shale, hydrates, tight sand, ultra tight sand and coal bed methane reservoirs serves as alternative sources to meet the increasing demand for energy all over the world. The exploitation of unconventional gas reservoirs has become an integral part of the global gas supply chain. The economic viability of many unconventional gas developments hinges on the effective stimulation of extremely low porosity and ultra-low permeability reservoir rocks. Global shale gas reservoirs are thought to contain large amount of natural gas resources and are therefore attractive targets for energy development. Global estimate of the gas originally in place in these reservoirs are quoted to be around 7,576.6 trillion cubic feet (TCF), while tight oil is estimated at about 418.9 billion barrels [1]. This huge energy resources need to be exploited for the benefit of sustaining global energy supply and the economy. Figure 1 shows global spread of technically recoverable shale gas reserves as at 2016 [2].

Shale gas reservoirs are organic-rich petroleum system wherein the same rock formation acts simultaneously as source, reservoir rock, sealing rock and the trap. Kerogen (organic matter) is the precursor for tight oil and gas in shale. The pores contain mature oil and gas Kerogen (organic matter) is the precursor for tight oil and gas in shale. The pores contain mature oil and gas Gas is stored in the limited pore space of the rock and migrates solely in a micro-scale. A sizeable fraction of gas is adsorbed on the organic materials [3-6]. Figure 2 shows Scanning Electron Micrograph (SEM) of kerogen rapped within organically rich shale [7]. Gas is highly dispersed in the micropores of the reservoir rock, rather than occurring in concentrated underground locations. Many studies and a lot of progress have been made on the development and production of shale gas reservoirs in North America, China and other countries, but the fundamental physics of flow in shale gas rocks and the engineering of fracturing shale gas reservoirs are not yet fully understood. It is therefore essential to develop a critical understanding of the factors that underlie the complex behavior of gas flow in the reservoir with a view to choosing the appropriate methods for optimal gas production from a given shale system.

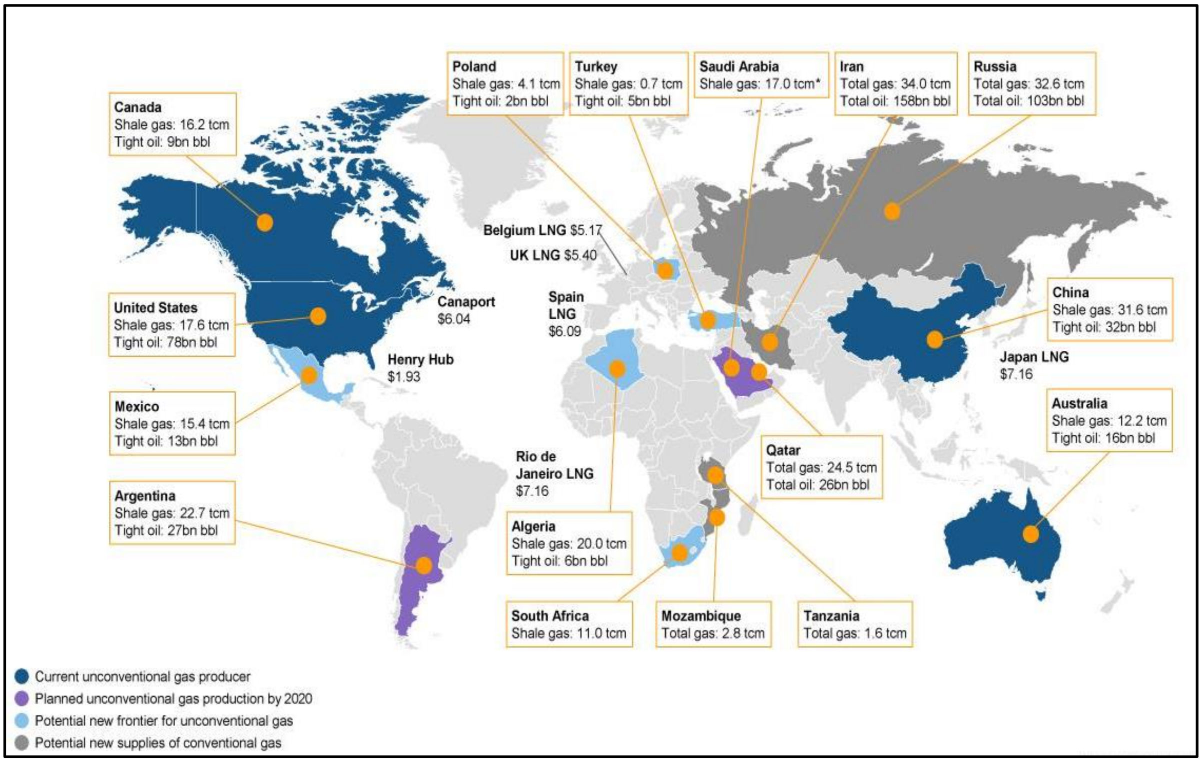


Figure 1. New supply landscape of technically recoverable reserves [2]

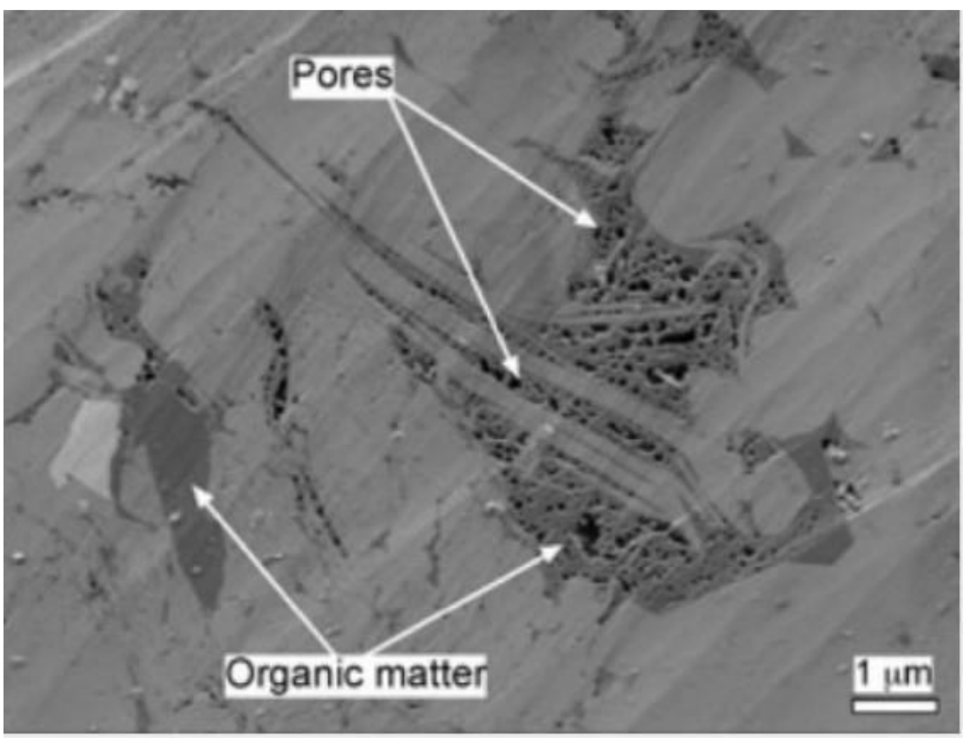


Figure 2. SEM of kerogen rapped within organically rich shale [7]

## 2. Technical issues

### 2.1. Petrophysical parameters: porosity and permeability

The reservoir parameters necessary for shale gas accumulations include thermal maturity, reservoir thickness, total organic carbon (TOC), adsorbed gas, free gas within the pores and fractures, porosity and permeability [8-9]. Thermal maturity is commonly measured in core analysis and reservoir thickness is routinely derived from analysis of logs. Shale gas reservoirs are complex and exhibit significant variations in their petro-physical characteristics (mineralogy, porosity, permeability, gas content, and pressure). In order to characterize the petrophysical properties of the rocks with regard to capability to accumulate and transport reservoir fluids, it is necessary to determine the values of these parameters, particularly porosity and permeability.

Porosity of shale gas formations is key parameter that directly affects the volume of gas initially in place in the reservoir. Together with the desorption characteristics of the shale rock, it plays very significant role in the gas delivery potential of the reservoir. There are three components of total porosity of a shale gas reservoir: porosity within natural fractures, which provide flow conduits to a wellbore, intergranular porosity, which contains electrochemically-bound water, capillary-bound water, and free fluids that are mostly presumed to comprise gas (intergranular porosity is non-zero in the (petrophysical) effective porosity system only if the shale is not electrochemically and compositionally 'perfect': it is always nonzero in the total porosity syste, and porosity associated with the organic content. Total porosity provides an estimate of the total gas in place [10].

Producibility of a shale gas reservoir depends greatly on permeability which is a key parameter for stimulation design and prediction of its flow capacity. Shale gas reservoirs have unique characteristics due to their very low and ultra-low permeabilities. Permeability is enhanced by the presence, density, and continuity of natural, open fractures [11]. Permeability is associated with the presence of natural cracks/fractures in the rock which enable the flow of reservoir fluids between pore spaces. Successful development generally entails hydraulic fracturing in order to connect these natural fractures to the wellbore. Permeability coefficient is dependent on the size of pores, relative configuration of the rock-building grains, grain grading and cementation, and rock fracture networks. Porosity and permeability in shales are highly dependent on mineral composition, organic matter distribution, quantitative (%) content of organic matter, and thermal maturity of organic matter. Shale rocks, because of their extremely low permeability (0.001 to 0.0001 mD), basically prevent any unrestrained flow of hydrocarbons and therefore stimulation (fracturing) must be performed in order to connect the pores to the borehole and allow for an unrestrained flow of gas.

### 2.2. Pore-network structure

Understanding of the internal structure of a shale rock sample is needed to calculate flow in the bulk system [12]. Numerical simulation methods, using X-ray computed microtomography (micro-CT) to scan internal structure of the rock sample from which a pore network is extracted, coupled with digital rock physics analysis (DRP), will be useful in characterizing the shale gas reservoir in terms of absolute and relative permeability and in quantifying the effects of the pertinent factors on multiphase flow and well performance for long-term gas recovery [13]. Knowing the pore network structure also helps in estimating other parameters such as spatial configuration of fluids in the pore spaces, wettability and its distribution, adsorption and desorption, precipitation and dissolution, biocide fouling and biomass growth. Molecular simulations have been gaining wide applications and are proving successful for the study gas adsorption in shale gas reservoirs.

### 2.3. Gas adsorption

Knowledge of gas transport process in shale matrix is of great importance in designing development strategies and in formulating appropriate predictive mathematical models for the complex multiphase behavior of the system. Knowing the contribution of each gas source to gas transport history and to ultimate gas recovery is of great importance to design and management of gas development project.

Gas desorption is essential in understanding the production capacity of a shale gas reservoir [14-18]. This is because, the shale can hold significant quantity of gas adsorbed on the surface of organic matter (including clay) in shale formations [19-20]. In shale, methane molecules are mainly on the carbon-rich components, eg kerogen, which is usually quantified in terms of total organic carbon (TOC). As the pressure decreases due to continuous gas production from the reservoir, more adsorbed gas is released from solid to the gas phase, contributing to flow and production. Mathematical models show that gas desorption rate varies and can be divided into three stages: slow desorption stage, the large desorption stage, and the final desorption stage [21]. It is critical to understand the multistage gas desorption process in order to adequately analyze shale gas transport phenomena and reservoir flow capacity necessary for designing production scheme for sustained economic gas recovery.

### 2.4. Geomechanics role

The effect of geomechanics is important and critical in gas production from shale formations. It is therefore necessary to properly characterize the geomechanical properties of a producing formation. Stress direction, optimum well trajectory and fracture orientation, relationship between matrix permeability, natural fracture permeability, and induced fracture permeability, and are of importance in designing stimulation schemes for increased gas production and minimization of environmental impact of fracturing operations Achieving reasonable gas production rates requires to significantly lower well pressure to maximize pressure drops in order to mobilize more gas to the well. This creates a large change in pressure field, leading to change in effective stress that may cause large rock deformation. As a result, the aperture and permeability of the micro channels and fractures is altered, leading to significant decrease in both fracture and matrix permeability and subsequent reduction in gas production [22-23]. Understanding the geomechanical behavior of unconventional shale gas systems throughout the production period is gaining increasing importance. Geomechanical analysis of the stress state in the reservoir leads to improved understanding of how to place and design wells for maximum gas production efficiency and project stability.

### 2.5. Shale gas reservoir simulation

The behavior of shale gas reservoirs and the complex fracture networks are mainly poorly understood. This poses a huge challenge for the petro-physicists who have to use more advanced techniques of research, especially in the nano- and macro-scale, and to the field engineers whose function it is to design effective stimulation schemes for economic development of the reservoirs. Different reservoir characterization methods for different scales are required for better understanding of individual shale gas reservoirs.

The last decade has witnessed increased studies and developments for shale gas reservoir resources [24-26]. Comprehensive review of flow mechanisms in unconventional shale gas reservoirs can be found in Blasingane [27], Gensterblum [28] and Wang *et al.* [29]. Commercial reservoir simulators and integrated workflow have been used to study gas production from shale gas reservoirs [30-32]. However, current understanding of gas flow and effective tools for the development of shale gas reservoirs is still far behind the industry needs. It is therefore very essential to identify the most critical parameters to be considered in shale-gas flow modeling for the development of stimulation tools adequate for a given reservoir.

## 3. Hydraulic fracturing and fracturing fluids

### 3.1. Hydraulic fracturing

Hydraulic fracturing has become a very common and widespread technique for practical exploitation of shale gas reservoirs. Figure 3 presents a schematic diagram of shale formation for natural gas. As the formation is fractured, gas flows from the non-Darcy scale to the complex fracture network and then to the well for production. According to Lee and Kim [33], the features that characterize the non-linear behavior of the reservoir flow dynamics include natural fracture system, adsorption/desorption of gas, diffusion in nano-pores, gas slippage (Klinkenberg effect), non-Darcy flow, and rock deformation caused by change in effective stress. Figure 3 shows a schematic depiction of hydraulic fracturing for shale gas [34].

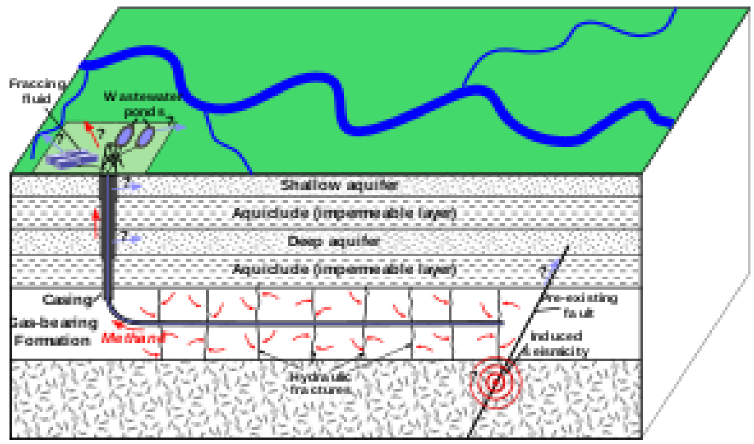


Figure 3. Schematic depiction of hydraulic fracturing for shale gas [34]

An improved understanding of hydraulic fracture geometry and shale rock mechanics enables reservoir engineers optimize stimulation design and completion strategy, improve stimulation performance, well productivity, and gas recovery. Gas production performance depends on nature and degree of fracture complexity fracture width: fracture spacing, and number of fractures. This is known as stimulated reservoir volume (SRV). A large stimulated reservoir volume (SRV) is very vital to enhanced gas production rate [35]. Simulation of the complex fracture network (natural and man-made) is a major problem for reservoir simulation approach. An adequate and valid simulation model is needed for sensitivity analysis of gas production- reservoir parameters relationship.

Hydraulic fracturing is performed by injecting fluid into a target rock formation at a pressure higher than the compressive strength or fracture pressure of the rock. The interval to be stimulated or fractured is isolated top and bottom with retrievable plugs and then pressured to rock breakdown pressure. The fractures formed stimulate the flow of natural gas or oil, increasing the volumes that can be recovered. However, the fundamental science and engineering of fracturing shale gas reservoirs are not yet fully understood and hence it is essential to develop a critical understanding of the factors that underlie optimal stimulation methods.

### 3.2. Hydraulic fracturing fluids

Hydraulic fracturing uses high pressure to force fluid consisting of water, sand and chemical additives into the shale formation. This pressurized fluid causes the rock to fracture, creating fissures or cracks in the formations. Gas (and oil) are released and flow through the fracture channels to the wellbore. Different types of chemical additives are added to fracturing fluids. These include: dilute acids, biocides, breakers, corrosion inhibitors, crosslinkers, friction reducers, gels, potassium chloride, oxygen scavengers, pH adjusting agents, scale inhibitors, and surfactants. Biocides are added to prevent microorganism growth and to reduce biofouling in the fractures; oxygen scavengers and other stabilizers prevent corrosion of metal pipes; and acids that are used to remove drilling mud damage within the near-wellbore area [36]. These fluids aid not only in creating the fractures but also they carry the proppants (sand, aluminum shot or ceramic beads) which frequently injected to hold the fractures open after the pressure treatment.

Figure 4 shows the level of baseline water stress in 20 countries with the largest volumes of technically recoverable shale gas resources. The volume of water injected during hydraulic fracturing affects the availability and consumptive use of freshwater resources, volumes of wastewater, the wastewater disposal and treatment procedures available, and the ultimate fate of this water [37]. Analysis of historical data indicates the importance of well borehole orientation, drilling date, and target gas resource on hydraulic fracturing water volumes [37] and could account for the wide range of estimates. Individually, these previous studies provided only partial information needed to fully understand the complexity of hydraulic fracturing water use across different geologic basins. There is a need to better understand the spatial variability of water use in hydraulic fracturing in aggregate, taking into consideration well types and target gas reservoirs.

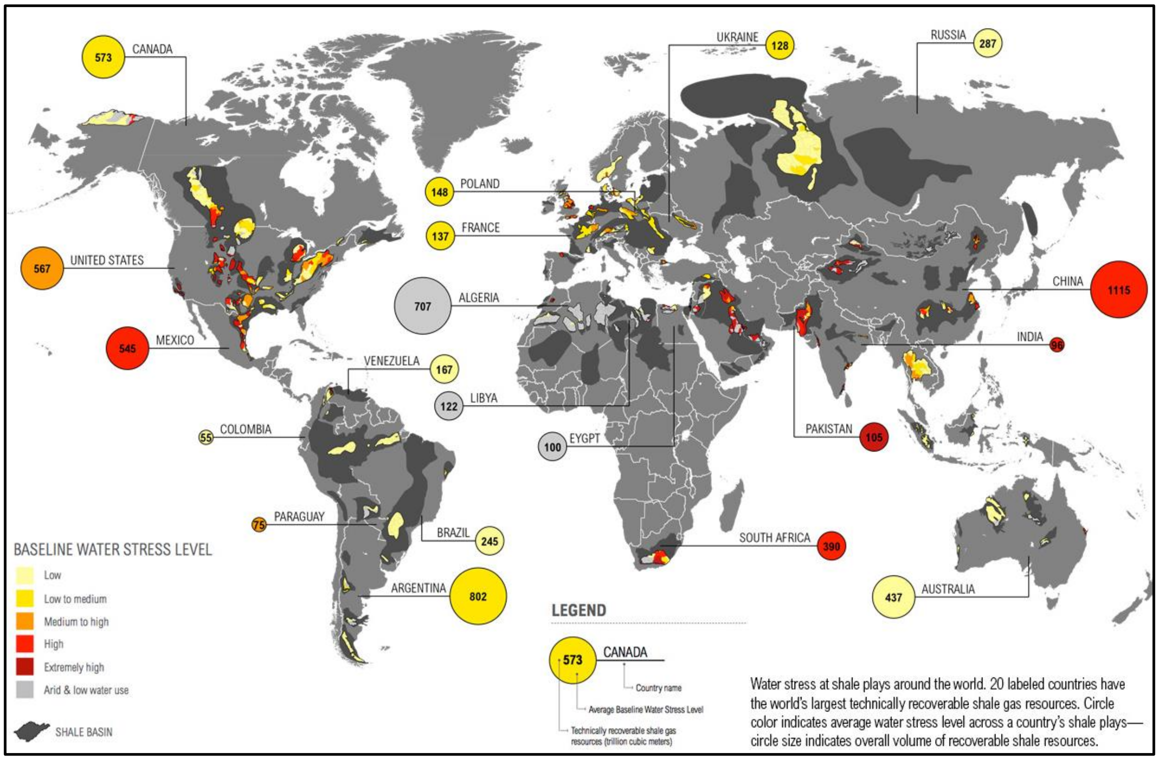


Figure 4. Baseline water stress level for hydraulic fracturing [38]

## 4. Environmental issues

### 4.1. Flowback and produced water

Although the make-up of fracturing fluid varies from one geologic basin or formation to another, the environmental issues associated with fracturing projects are the same or similar. These include water and soil contamination that result from the processes and handling of the fluids as well as the large quantities of water necessary to undertake fracturing and seismic activity that might be induced. Large volumes of freshwater are mixed with the above stated chemical additives and proppants in varying quantities depending on the geological location or well and reservoir properties. Millions of gallons of water may be injected per site, generating very large volumes of flowback and produced waters. Flowback waters are those that return to the surface after the pressure is released. They are extremely complex matrices composed of hydrolytic fracturing fluids and chemical additives chemical additives that were injected and the recovered hydrocarbons from the deep formations, highly saline, with large amounts of total dissolved solids. They may contain various hydrocarbons, organic acids, alcohols, radionuclides, and metals. Figure 4 shows global baseline water stress level for hydraulic fracturing in the 20 countries with the largest shale gas and tight oil resources, as analyzed by World Resources Institute [38]. For shale gas, it was found that 40 percent of these countries face high water stress or arid conditions: China, Algeria, Mexico, South Africa, Libya, Pakistan, Egypt, and India

The large volumes of water used in fracturing invariably leads to large volumes of wastewater produced and ultimately to potential environmental impacts, including public water availability, water quality, wastewater disposal, aquatic ecology, and possible wastewater injection-induced earthquakes ecology [39-44]. More localized and technology-specific risks are coupled with degradation of air quality and water resources, induced seismic activity, and methane emissions which can increase the overall risk of climate change due to their increased potency relative to other fossil fuels [45].

On a regional basis, the average water volume used per well for hydraulic fracturing will depend on the number and locations of wells accessing shale gas reservoirs within a geologic basin [37]. Differences in local geology, well borehole configuration, resource type, target gas reservoir characteristics, well completion time, hydrology, and proximity to freshwater sources, existence and location of water treatment facilities, chemical makeup of flowback and produced wastewaters, management practices, land availability for surface storage, and availability of deep-disposal wells, coupled with differences in volumes of water injected could translate into possible differences in the potential for environmental impacts [46]. Development of better technological approaches that will serve as potential solutions to the problems posed by the complex matrices inherent to flowback and produced waters is needed.

### 4.2. Wastewater composition

Apart from the chemical additives to be managed, the natural water that is surfaced may contain very high levels of dissolved solids (TDS), toxic metals, radionuclides and hydrocarbons. In addition to the high content of sodium and chloride, the salts content can include elevated concentrations of bromide, bicarbonate, sulfate, calcium, magnesium, barium, strontium, radium, organic chemicals and heavy metals. The management challenge is to safely dispose, treat, or reuse those waters without damaging the local groundwater or downstream surface waters and potential drinking water sources [47-48].

The number of hydraulic fracturing shale oil and gas wells in the US, and worldwide, continues to increase. This will result to increased stress on surface water and groundwater supplies to complete the fracturing process. Equally important is the large volumes of wastewater generated (up to 60% of the water injected into a well) as flowback or produced water during fracturing of wells. This wastewater needs to be captured, and disposed of or recycled.

Water being the base fluid and biggest component used in hydraulic fracturing, its importance remains a critical factor in the operation and economics of shale oil and gas production. However, significant and growing water management challenges are impacting hydraulic fracturing [49-51]. Therefore, oil and gas companies, faced with growing concern of proper water utilization activities, need to adopt a more unified and proactive perspective on their water life-cycle management.

With the already significant fracturing industry set for further rapid expansion in the US and other countries, the demands on fresh water supplies are mounting, as is the need to process the large volumes of flowback and produced wastewater discharged during fracturing operations. Centralized treatment of wastewater is emerging as a viable solution for long-term efficiency in managing water sources and wastewater treatment in hydraulic fracturing [52].

A word on regulatory requirements – the type of chemical additives to be used in hydraulic fracturing projects and the information about their chemical characteristics should conform to regulatory requirements. Material Safety Data Sheets should be provided by the additives manufacturers [44]. Also to be provided are:

- the potential health and environmental risks of each of the additives be assessed by the operating company or suitably qualified third party selected by the operating company;
- operationalproceduresand controlsspecific to the selected additive(s) determined to manage the potential health and environmental risks identified by the risk assessment, as appropriate;
- written risk management plans incorporated into the well-specific hydraulic fracturing program;
- confirmed execution of the risk management program and actual additives used prior to program initiation and at program completion.

## 5. Conclusion

After many years of unconventional shale gas development and production the industry is not grappling with technical and environmental issues that impact on economic gas production. Existing science and technology data on shale gas formations are not adequate for describing complex flow and transport phenomena occurring in the reservoir. More research is needed to help improve understanding of the peculiar characteristics of individual shale gas reservoir adequate for determining stimulation technologies for economic gas development and recovery. Numerical simulation methods, coupled with digital rock physics analysis (DRP), will aid in characterizing individual shale gas reservoirs and quantifying the effects of pertinent factors on multiphase flow and well performance for long-term gas recovery. Knowledge generated from such studies will enable engineers to better design fracture treatments and operators to better manage the wells in a shale gas reservoir.

Regional variations in regulatory structures also mean that decisions regarding hydraulic fracturing including wastewater management and disposal practices, recycling, and underground fluid injection may fall under different regulations and jurisdictions. Because hydraulic fracturing is not a one-size-fits-all operation, assumptions and generalizations regarding water use in hydraulic fracturing operations and the potential for environmental impacts should be made with caution. More efforts are needed to develop a one-stop approach to managing environmental issues associated with freshwater usage for hydraulic fracturing operations and for managing the large volumes of flowback and produced waters generated in fracturing projects.

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