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A Critical Review on the Advancements in Exploration and Production of Shale Gas

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Abstract: The exploration and production of shale gas have seen significant advancements in recent years, driven by the increasing global demand for clean energy sources. These advancements encompass the understanding of a wide range of areas, including the formation theory of shale gas reservoirs, evaluation methods, well drilling, completion, and simulation techniques. Innovative design, modelling, and field practices have been developed for shale gas well drilling and completion, as well as its production techniques. Furthermore, new simulation techniques, software, algorithms, and other tools have been introduced to improve the modelling and simulation of shale gas production. Experimental and simulation research in shale gas exploration, development, and production using hydraulic fracturing has also seen considerable progress. These advancements are contributing significantly to the global demand for clean energy sources with a promise to achieve sustainable development goals. This review work explores the exploration and exploitation of shale gas with a detailed description of multidisciplinary research efforts, providing valuable insights into shale reservoir/rock characterization and geo-mechanics, fluid-surface interactions, gas adsorption behaviours and single- and multi-phase flow mechanics. These advancements are not only increasing the efficiency and productivity of shale gas extraction but also paving the way to meet the future global energy demand while also contributing to the goal of achieving net-zero carbon emissions. The novelty of the review work is that it exhibits a combined qualitative and quantitative study of recent advancements in the sphere of exploration and production of shale gas reserves and its discoveries around the globe.

Introduction

Initially, oil and gas were extracted from conventional reservoirs with good porosity and permeability. However, it was later found that about 50% of the available hydrocarbons were trapped in less porous and permeable rocks called unconventional reservoirs, as shown in Figure 1, which required new technologies such as hydraulic fracturing to extract them (Tomiwa et al., 2022). In the past, extracting oil and gas from unconventional reservoirs was not considered cost-effective due to the lack of technology. However, with the development of technologies such as directional drilling and hydraulic fracturing, trapped reserves of oil and gas can now be recovered from these reservoirs. Unconventional gas reserves are estimated to be eight times greater than conventional gas reserves, with a global resource of around 3,921E+12 m^3 (Al-attar and Barkhad, 2019). Subsurface assessments carried out in China found abundant resources of unconventional natural gases, 8.8×1012 m^3 to 12.1×1012 m^3 of recoverable resources of tight gas, 15×1012 m^3–25×1012 m^3 of recoverable resources of shale gas, 10.9×1012 m^3 of recoverable resources of coal bed methane were detected (Jia et al., 2022). Similar positive results of

*Corresponding Author: prasenjit_duiet@dibru.ac.in abundant unconventional natural gas were found around the globe. By the first half of the 21st century, it is predicted that the demand for Natural Gas (NG) will increase tremendously in countries like India, China, Japan, South Korea and Taiwan.

So, the exploitation of unconventional NG reservoirs can help us meet the ever-increasing energy demand in the world. Unconventional NG can be classified as shale gas, Coal Bed Methane (CBM), gas hydrates and tight gas. However, this paper aims at a comprehensive review of varied prospects of Shale Gas. Shale gas is found trapped in the less porous, less permeable, deeper shale rocks in the subsurface (Melikoglu, 2014; Yunna and Yisheng, 2014; Dong et al., 2016; Zio et al., 2017) and has a comparatively lower heating value than the conventional NG (Demirbas et al., 2018). It has high gas-supplying capacity, no channels for primary or secondary migration and it belongs to the intra-source unconventional gas accumulation system (Al-attar and Barkhad, 2019). Development of technologies like horizontal drilling and HF has revolutionised shale gas exploration in different parts of the world, including North America, China etc. (Zhang et al., 2022). While hydraulic fracturing has enabled exploration companies to recover residual oil from unconventional systems, it has drawbacks such as the need for a large amount of water-based fluid, long clean-up time, formation damage, and excessive wastewater production (Zhang et al., 2022; Middleton et al., 2015; Lyu et al., 2018).

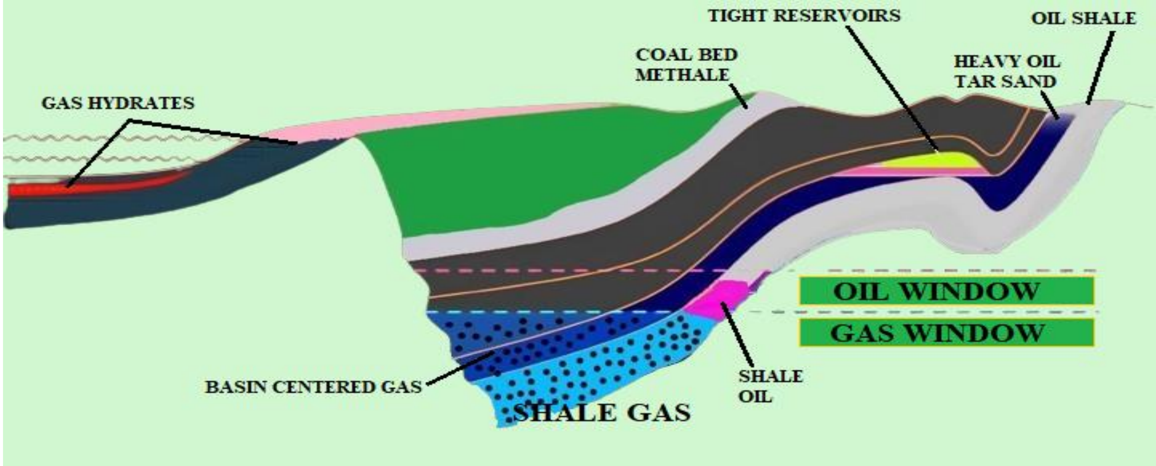

Figure 1. Illustration of various forms of unconventional hydrocarbon systems and their relationships to conventional hydrocarbon systems (Scotchman 2016a)

Shale gas, a clean energy source in fossil fuels, has seen significant advancements in its exploration and production in recent years. With the increasing global energy demand and the gradual depletion of conventional reservoirs, the role of shale gas has become increasingly crucial. In fact, shale gas production accounted for approximately 80% of total dry gas production in the United States in 2022. The advancements in shale gas exploration and production are largely attributed to a range of advanced technologies such as geological desert, well factory, and hydraulic fracturing (Silva et al., 2017). These technologies have not only increased the efficiency of shale gas production but also made it more environmentally friendly. In the context of climate change and the goal of achieving carbon neutrality, shale gas development is facing new challenges. However, the strong power for the increase in shale gas production is due to advanced, efficient and environmentally friendly technology. The uniqueness of this review work is that it provides a qualitative and quantitative analysis of recent research on shale gas reserves and discoveries worldwide. It comprehensively examines the functional properties of shale gas, recovery techniques, problems, and solutions associated with production operations, such as hydraulic fracturing. Additionally, the study highlights potential shale gas reserves globally.

Conventional and Unconventional gas reservoirs

Pang et al. (2021) and Silva et al. (2017) mentioned that unconventional gas reservoirs include tight gas, CBM, shale gas, and gas hydrates. Advanced technologies like horizontal drilling, dewatering, and hydraulic fracturing are needed to extract gas from non-porous and impermeable rock. Unconventional and conventional reservoirs can coexist in the same basin, with the unconventional acting as the caprock for the conventional (Pang et al., 2021; Silva et al., 2017). Aguilera et al. (2014) in their paper mentioned conventional gas is typically found in easily extractable formations that are porous and permeable, such as sandstone and carbonate reservoirs in sedimentary rock. These formations are part of the petroleum system and are often capped by shale, carbonate rocks, or evaporates. Natural drive mechanisms are used to bring the gas to the surface, but artificial lifts, water flooding, and enhanced oil recovery methods may be used later in production. These reservoirs do not require additional stimulation to enhance porosity and permeability, making them economically viable (Aguilera et al., 2014). Pang et al. (2021) mentioned conventional petroleum reservoir occurrence in basins is dependent on multiple factors, including tectonic activity, source and reservoir properties, driving forces, and formation mechanisms. Reservoirs were classified into structural and non-structural traps and categorized into five types based on differences in trap and formation mechanism: anticlinal, faults, lithology, stratigraphic, and hydrodynamic trap reservoirs. Buoyancy-driven conventional traps were identified as the main reason for hydrocarbon accumulation (Pang et al., 2021). According to Wallaker (2013) over 50% of the world's oil and gas reserves are located in the Persian Gulf area due to the Tethys Seaway's location. Iran, Qatar, Saudi Arabia, and the United Arab Emirates have the largest reserves. North America holds the second-largest reserve, while the rest of the world has only 28%. The Middle East has 37% of the world's natural gas reserves, and Russia holds the second-largest share of 27%. The Tethys Seaway's closure created structural points that became cap rocks, allowing for oil and gas accumulation in the reservoir. Unconventional gas resources mainly include Coalbed Methane (CBM), Gas hydrates and Shale gas. Coalbed methane is found in coal seams at depths of 200-1000m, with global reserves of 110-200 Tm^3. Canada, Russia, and China have the largest reserves. Methane hydrates have reserves of 0.5-2.5×1012 tons, which require alternative extraction methods. Traditional recovery methods cannot extract gas from hydrates, so alternative techniques such as reducing pressure, thermal methods, and chemical injection are used. Shale gas, composed mainly of methane, is found in shale rocks with low porosity and permeability. HF is used to create fractures and improve permeability (Aguilera et al., 2014). There are 48 major shale basins in 32 countries with an estimated global reserve of 716 Tm^3 according to the International Energy Agency.

Differences between conventional and unconventional reservoirs

According to Zou et al. (2018) conventional reservoirs differ from unconventional reservoirs in their structural location, with conventional reservoirs typically found higher and further from their source compared to unconventional reservoirs. Conventional reservoirs have well-defined trap boundaries and hydrodynamic effects, whereas unconventional reservoirs have unclear trap boundaries and are spread across slopes and depression zones near their formation zone (Zou et al., 2018). Silva et al. (2017) compared conventional and unconventional reservoirs in six representative petroleum basins in China. Their study found differences in HC compositions, spatial relationships to source rocks, reservoir lithology and quality, distribution in geological settings, and reservoir formation mechanism (Silva et al., 2017). Conventional reservoirs were found to contain lighter gas than unconventional reservoirs due to differences in distance from the source rock and tectonic deformation. Conventional reservoirs were far from source rocks in the vertical direction, while unconventional reservoirs were near or embedded within the source rock. Reservoir lithology and properties varied, with shallow burial conventional reservoirs having higher porosity and permeability and greater depth reservoirs having less. Different tectonic settings were responsible for forming conventional and unconventional reservoirs, with different dynamic mechanisms driving HC accumulation. Lastly, the authors proposed a unified genetic classification scheme for different reservoirs based on their similarities and differences. Pitcher et al. (2011) mentioned that steering techniques differ between conventional and unconventional reservoirs. Geosteering is used to guide the drill bit to the target zone and construct the wellbore. Traditional tools like resistivity and gamma logs are used, but sonic logging is more useful when resistivity contrasts between layers decrease. For conventional reservoirs, deep reading azimuthal resistivity and gamma log are commonly used, while for unconventional reservoirs, azimuthal sonic measurements are more successful in describing thin rock layers. Unconventional reservoirs require Enhanced oil recovery (EOR) techniques to recover the residual hydrocarbons left after primary and secondary recovery stages. EOR techniques like surfactant flooding, polymer flooding, and steam flooding are essential for this (Pitcher et al., 2011). Isaac et al. (2022) conducted an experimental study to select suitable surfactants for EOR and their application to both conventional and unconventional reservoirs (Tomiwa et al., 2022). Previous studies mainly focused on low-temperature and low-salinity conventional reservoirs, where sulfonate surfactants were commonly used. However, sulfonate surfactants were found to be unstable in high or ultra-high temperature, high salinity unconventional reservoirs. Zwitterionic surfactants were found to be more suitable for surfactant flooding in unconventional reservoirs due to their thermal stability and ability to resist high salinity and hard brine.

The study showed that additional oil recovery using surfactants in unconventional reservoirs ranged from 6% to 28% of HIIP, with some cases reaching up to 50% of HIIP.

Exploration and production of Shale gas

Shale gases are stored in unconventional reservoirs, specifically shale reservoirs, where gas is adsorbed on the walls of organic matter and clay minerals. However, shale's low permeability and porosity make it difficult to extract HC using traditional methods. In contrast to conventional reservoirs, shales in unconventional reservoirs act as cap rocks. To increase permeability and extract resources, new techniques like hydraulic fracturing through horizontal wells are utilized.

Understanding the shale gas reservoir before production operation

Scotchman (2016) mentioned that a comprehensive understanding of shale reservoir mineralogy is vital for successful shale gas production through hydraulic fracturing (HF). Shale reservoirs consisting of brittle minerals like silica and carbonate are favourable for efficient fracturing, whereas those composed of clay-rich ductile minerals are not. Silica and carbonate-rich shale reservoirs in North America, such as Barnett, Marcellus, Mowry, and Duvernay Shale Formations, are predominantly silica-rich, while the Eagle Ford, Niobrara Formations, and Vaca Muerta Shale formation in Argentina are carbonate-rich shales. The Haynesville Shale formation in the US is a mixed siliceous-calcareous shale. To ensure efficient exploration and production of shale gas, the shale must be organic-rich, have substantial regional presence and thickness, and have suitable thermal maturity and depth. The average shale gas producing depth in the US ranges from 1000 to 4000 m, with production outside this range leading to potential groundwater contamination, seismic activity, or economic challenges. Geological data evaluation, including mineralogy, geochemistry, and seismic data analysis, combined with micro-seismic measurements of the fracking process, can accurately identify shale gas sweet spots and determine the volume of gas in the reservoir (Scotchman, 2016b). Mu and Zhang (2012) discussed the use of numerical simulation models incorporating micro-seismic measurements to improve understanding of well performance in shale reservoirs. The wire-mesh, discrete fracture, and dual-porosity models were evaluated, and the authors found that reservoir modelling enhanced the understanding of shale gas reservoirs. Complex fracture models, combined with micro-seismic measurements and reservoir simulation, provided a better evaluation of hydraulic fracture characteristics and production potential in shale reservoirs (Chengzao et al., 2012). Nguyen-Le et al. (2021) analysed 546 shale gas datasets from the Barnett reservoir to investigate the relationship between early production data and the long-term cumulative gas production (CGP) at various time intervals. They developed a 5-step process to create a shale gas production forecast model using two approaches: multivariate polynomial approach and response surface methodology. Among the four models developed, MP-1 and RSM-2 were found to be the most effective in predicting CGP. RSM-2 was used to predict three-year production while MP-1 models were used for five-, seven-, and ten-year production. The multivariate polynomial forecast model was found to be efficient and reliable, with minimal errors and a strong relationship between early and long-term production (R2 > 0.99). Field applications of the model also showed positive results (R2 > 0.80) (Nguyen-le et al. 2021). *Tripoppoom et al. (2020)* in their paper selected three shale gas wells to investigate the difference in production performances with different completions and fracturing designs. Assisted history matching using neural networks Markov chain Monte Carlo algorithm was used to perform production match automatically and multiple history matching solutions were obtained. Their findings showed that reservoir parameters like fracture half-length, fracture conductivity, fracture width, and matrix permeability differ significantly in the three wells, while parameters like fracture height, fracture water saturation, porosity and relative permeability curves were almost identical in all the wells. These findings could be extremely useful for investigating new fracture treatment designs to improve any future fracturing wells (Tripoppoom et al., 2020). The estimated ultimate recovery (EUR) of the three wells was also forecasted by the authors as shown in Table 1.

Table 1: Summary of gas EUR forecast of the three selected wells (Tripoppoom et al., 2020).

Well parameters	Well A	Well B	Well C	Unit
20-year gas EUR	3507	3261	4669	MMscf
30-year gas EUR	3859	3552	5103	MMscf
20-year gas EUR per cluster	49	39	86	MMscf per cluster
30-year gas EUR per cluster	54	42	95	MMscf per cluster

Xia et al. (2021) studied the self-diffusion flow of deep shale gas at different temperatures and the impact of bottom hole temperature on HC recovery from deep shale gas reservoirs using a self-diffusion flow and heat coupling model. The authors used the model to simulate

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the production of a shale gas well in the Sichuan Basin and found that the model accurately predicted gas production when temperature changes were considered (Yang et al., 2021).

Enhancing the production of shale gas

Wang et al. (2019) investigated the effect of electrical resistance heating on shale gas production (Wang et al., 2019). Mathematical models were formulated and solved using a finite difference method. Two parallel horizontal electrodes of length 100 m placed 100 m apart as shown in Figure 3 were used to heat the formations. The cumulative gas production (CGP) was compared before and after heating, and the results showed an increase of 7.27%, 14.67%, and 20.04% after 20 years, 40 years, and 60 years, respectively as shown in Figure 2. Thermal conductivity was found to be important, as CGP decreased by 1.60% and 3.62% when the heat conductivity increased from 1.20 W/(mK) to 2.312 W/(mK) and 4.75 W/(mK), respectively. A decrease in the heat capacity of the formation was beneficial, with a 5.28% and 13.06% increase in CGP observed when the heat capacity decreased from 4.08 x 106 J/ (m^3 K) to 2.04 x 106 J/ (m^3 K) and 1.02 x 106 J/ (m^3 K), respectively, at the end of 40 years. Higher Langmuir volume was also found to be beneficial, with a gas production increase of 10.43%, 14.84%, 18.49%, and 21.83% observed when Langmuir volume increased to 5.0, 10.0, 20.0, and 30 m^3/m^3, respectively as shown in Figure 4. More electrical power and longer electrode length were also found to yield higher gas production, with 50 kW, 100 kW, 200 kW, and 300 kW electrical powers increasing gas production by 0.70%, 14.66%, 26.11%, and 34.88%, respectively. Longer electrode lengths of 60 m, 80 m, 100 m, and 120 m also yielded an additional gas production of 12.2%, 13.7%, 14.6%, and 14.8%, respectively as shown in Figure 5.

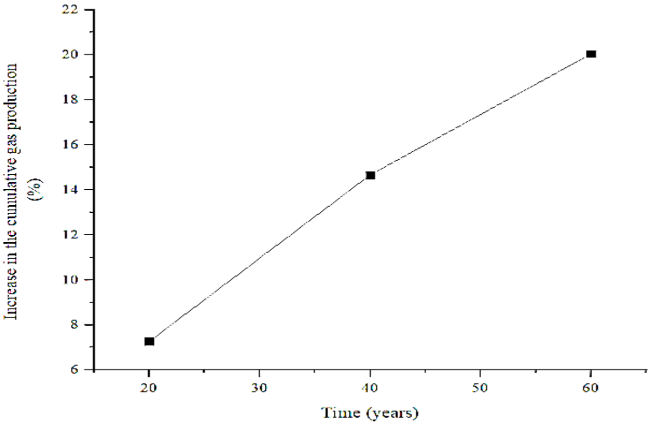

Figure 2. Shows the increase in the cumulative gas production due to electrical resistance heating (edited from Wang et al., 2019).

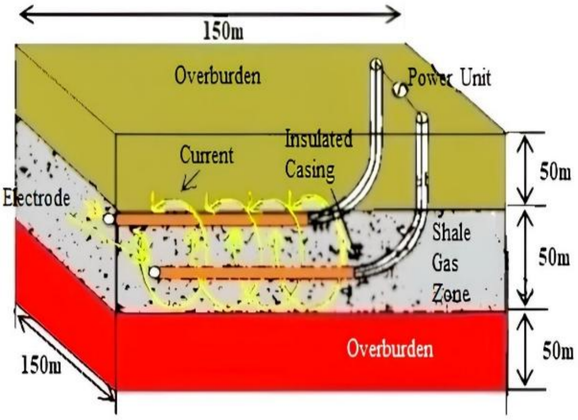

Figure 3. Shows the parallel and horizontal electrode configurations used by for heating the shale gas reservoir to enhance the gas production (Wang et al., 2019).

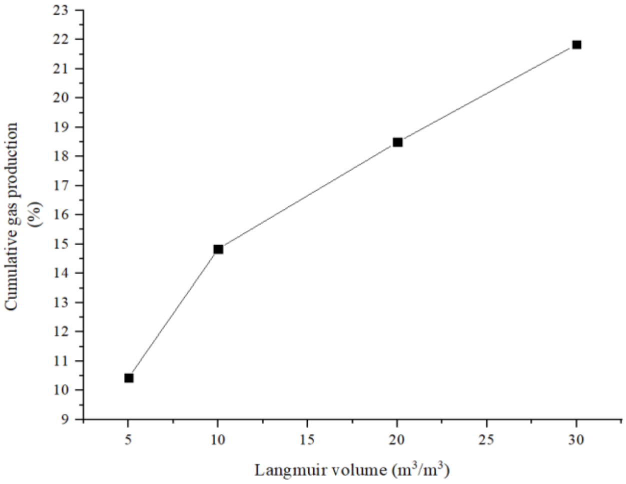

Figure 4. Shows the increase in the cumulative gas production with an increase in Langmuir volume (edited from Wang et al., 2019).

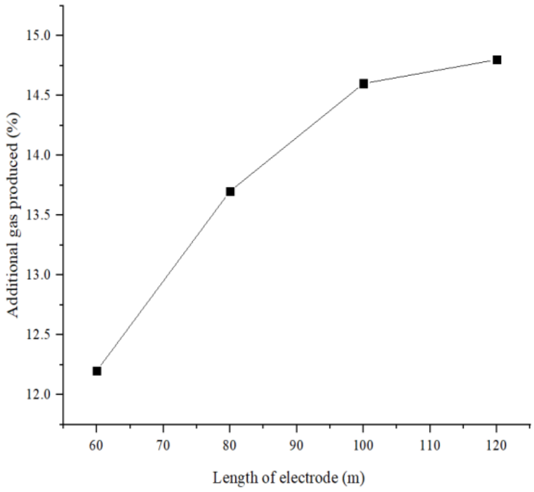

Figure 5. Shows the additional gas produced due to an increase in the length of the electrode (edited from Wang et al., 2019).

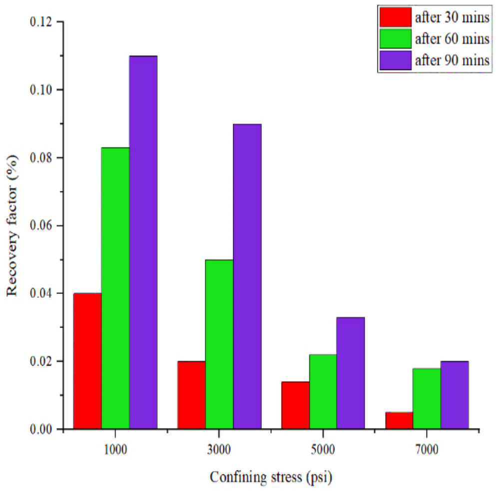

Figure 6. Shows the increase in the recovery factor before and after the treatment at different confining stresses (edited from Wang et al., 2019).

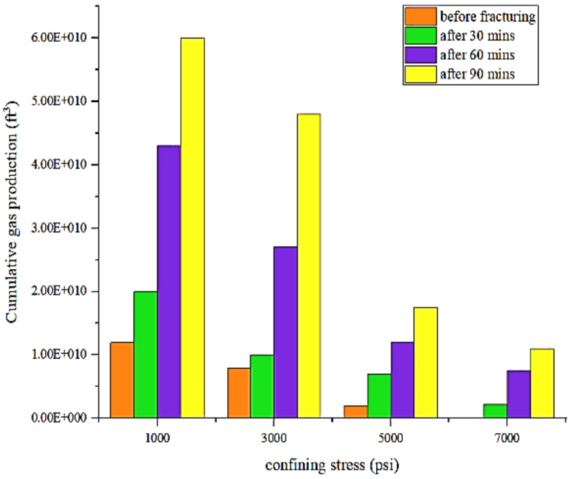

Figure 7. Shows the increase in the cumulative gas production before and after the treatment at different confining stresses (edited from Memon et al., 2021).

Fianu et al. (2020) investigated the impact of microwave heating on shale gas reservoirs to increase production. The authors developed a model that coupled electromagnetic and thermal effects to simulate the process near the perforated zones. After validating the model, they found that the production rate increased by 25% after a year of heating. The highest temperature increase occurred at the centre of the reservoir, decreasing at surrounding nodes. The authors tested three different heating frequency ranges and found that 915 MHz was the most effective in increasing production (Fianu et al., 2020). Chen et al. (2020) also examined the impact of microwave heating on porosity and permeability of shale reservoirs (Chen et al., 2021). The authors used two shale samples to analyse the effect of microwave irradiation on permeability at varying effective stress.

They discovered that porosity increased from 1.57% to 3.83% due to thermally induced stresses and chemical-transformation-induced gas pressures. They also discovered that the duration and temperature of microwave irradiation played a role in increasing shale permeability, with temperatures above 325°C leading to a rapid rise (Chen et al. 2021). Memon et al. (2021) conducted a study on using cryogenic liquid nitrogen (LN2) treatment to enhance shale gas production from Mancos’s shale formations. They immersed core samples into liquid nitrogen for 30, 60, and 90 minutes and observed an increase in fractures and connectivity, with the highest increment after 90 minutes. Numerical simulation was performed at different confining stresses and times for each treatment, resulting in an increase in porosity, permeability, fractures, and gas production rates. The highest recovery factor, as shown in Figure 6 was 11% after 90 minutes of treatment under 1000 psi confining stress. The cumulative gas production, as shown in Figure 7 after treatment was found to be 6.0×1010 ft^3 for 90 minutes under 1000 psi confining stress. Sherratt et al. (2021) examined the impact of natural fractures and well orientation on gas production from hydraulic fractured shale formations using a Fracture Upscaling Model (FUM). The base well had a standard well orientation (θw = 90°) and a well spacing (Sw) of 300 m. Results showed that hydraulic fractures can propagate in directions other than the maximum horizontal stress (σhmax) direction, resulting in poor formation connectivity between wells. Changing the well orientation was found to increase recovery by 10–20% for natural fracture angles (θnf) close to 80° and 60° but had no effect for θnf = 40°. Well orientation changes were advantageous when the natural fractures formed an angle close to 90° with σhmax but failed when the natural fractures existed in two perpendicular planes with equal distributions (Sherratt et al., 2021). Kovalchuk and Hadjistassou (2021) in their study used a numerical model and an actual shale scanning electron microscope (SEM) micro-image to understand the mechanism behind gas production from shale. The non-dimensional cumulative production data of the model matched core measurements more accurately than other methods. Two cases were analysed as shown in with different gas compositions: 70% methane and 30% ethane resulted in non-dimensional cumulative production around 1900, 100% ethane resulted in around 2200, and 100% methane resulted in around 1700 (Kovalchuk and Hadjistassou, 2021).

Exploration and production of shale gas reserves around the world.

Practical experiences from the last ten years of exploration and development processes of shale gas in the Wufeng-Longmaxi Formation in China were discussed by Yongsheng et al. (2018) and based on that the authors also suggested some future development techniques. The recoverable amount of shale gas in China was 10.50×1012 m^3 in 2011. By the end of 2017, China had a proven shale gas reserve of around 1 trillion m^3, and shale gas production increased to 9 billion m^3. Over 600 billion m^3 of the cumulative gas reserve was found in the Fulin shale gas field, and there was a proved shale gas reserve of more than 300 billion m^3 cumulatively. The daily shale gas production in the Changning region rose to 15×104 m^3 from the Wufeng Formation and the Longmaxi Formation. Shale gas production of 3 billion m^3 was also discovered in the Weiyuan, Changning, and Shaotong in Chuannan region in the year 2017. Fast drilling of horizontal wells, pumping bridge plugs and clustered perforation for multistage fracturing, simultaneous fracturing, and chain fracturing are the emerging technologies currently used for the exploration of shale gas (Yongsheng et al., 2018). Wang et al. (2019) analysed the Tanezzuft shale's gas exploration potential by comparing it with the Longmaxi, Marcellus, and Barnett shale plays. The net pay thickness, total organic carbon, thermal maturity, burial depth, and fault locations were mapped to predict shale oil and gas distribution in the Ghadames basin. The study found high TOC with less burial depth and decreasing TOC from north to south. The thermal maturity was 0.7%-2.0%, and the shale burial depth was 2000 to 5000 m. The gas distribution was comparable to the Barnett, Marcellus, and Longmaxi shale plays. The study estimated a total recoverable shale gas potential of 4.9 trillion m^3 for the Tanezzuft shale formation (Wang et al., 2019). Liang et al. (2021) in their study focused on shallow shale gas reservoirs buried at a depth of 700 to 2000 m in the Taiyang anticline area in the Zhaotong demonstration zone. The authors studied three marine shale formations and discovered a continuous gas-bearing area of about 580 km2. Shale gas exploration in the region started in 2009 with the drilling of Well YQ1. Shale gas was discovered in nanopores in April 2017, leading to the drilling of 13 more wells. The shallow shale gas had a total gas content of 3.81–5.34 m^3/t, and vertical wells and horizontal wells had production capacities of (0.5–2.0) × 104 m^3/d and (2.63–20.70) × 104 m^3/d, respectively (Liang et al., 2021). Chen et al. (2020) analysed the production potential of China's Wufeng-Longmaxi shale gas formation using the Difference-Index (DI) analogy and simulation methods. The authors compared the characteristics of five US shale plays and found that the Haynesville play was the closest analogue. They established three drilling plans using simulation models and found that China's shale gas production had the potential to reach 70 Bcm/yr with better technology and more wells. The drilling plans showed peak production of 200 MMcm/d with a total of 7200 wells, an increase from 70 MMcm/d to 174 MMcm/d from 2020 to 2035 with a total of 1058 Bcm gas, and a plateau production of 65 Bcm/yr with a total of 9400 wells resulting in 1251 Bcm gas production from 2020-2050 (Chen et al., 2020). Patzek et al. (2013) developed a model using scaling theory that could accurately determine the amount of gas that can be produced from 8,294 wells in the Barnett Shale. The model was used to establish lower and upper bounds on gas that could be produced from the wells; they estimated that the ultimate recovery from the 8,294 wells in the Barnett shale play was between 10 and 20 trillion standard cubic feet (Patzek et al., 2013). Male et al. (2015) used the methods developed by Patzek et al. (2013) to determine the well decline curves and productivity for the wells in the Haynesville shale play. The authors modified the original model to account for early-time throttling of wells and determined gas properties in the reservoir using a custom PVT solver. They applied the model to over 2000 wells in the Haynesville shale play and found that 1,546 wells had experienced inter-fracture interference within a year, with an estimated permeability of 240 nano Darcy and an expected ultimate recovery of 3.24 Bcf for median wells. For wells that had not yet exhibited interference (618 wells), the authors estimated the time to interference and calculated a EUR of 3.97 Bcf over 25 years (Male et al., 2015).

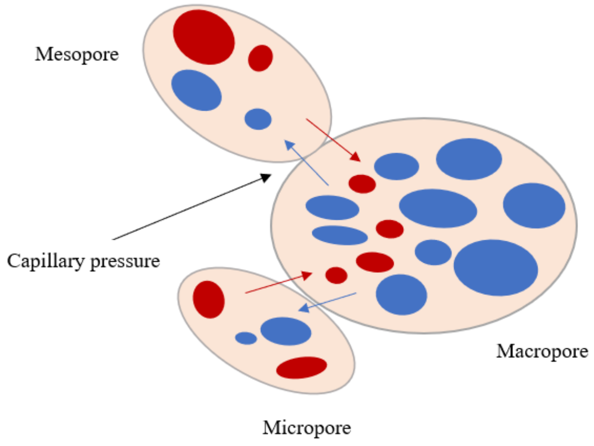

Figure 8. Shows the aqueous phase redistribution, migration from the macropores to the smaller pores, reduction in the capillary discontinuity and creation of channels for oil flow during shut-in (Li et al., 2019).

For the purpose of enhancing the efficiency of shale gas exploration, it is necessary to apply new technologies such as fast horizontal drilling and multistage fracturing as in the case of Wufeng-Longmaxi Formation. As demonstrated by Patzek et al. (2013) and Male et al. (2015), advanced reservoir modeling can help in the prediction of the recovery of the gas and the management of the wells. Chen et al. (2020) and Wang et al. (2019) have also pointed out that the optimization of the strategies based on the geological characteristics, the enhancement of the well density and the investment in the environmental measures will also enhance the potential of shale gas while reducing the negative effects on the environment. Also, the operators should focus on the effectiveness of the regional approaches to water management to counter the environmental impacts of hydraulic fracturing. Especially due to the fact that shale resources are abundant and, in some regions, considered as a domestic source, it will only be possible to sustain the reserves for the long term if new drilling techniques are developed and the focus is put on sustainable development.

Hydraulic fracturing and associated challenges

Scotchman (2016b) discussed hydraulic fracturing (HF) as the most common well-stimulation technique used in shale gas production. This process involves injecting a fracking fluid, primarily composed of water, at a pressure exceeding the reservoir rocks' fracture gradient. This creates artificial fractures and enhances the rock's permeability. Proppant particles are added to keep these fractures open, along with small quantities of gels, friction reducers, cross-linkers, and surfactants. However, this technique can cause water invasion, which reduces the rock's permeability. To address this issue, production is temporarily halted to allow the water to seep into deeper formations (Scotchman, 2016b). Li et al. (2019*)* investigated water invasion during hydraulic fracturing and the restoration of reservoir permeability after shut-in. They used a 4-step core flooding system and NMR to evaluate the permeability and aqueous phase migration in rock samples. The experiment used synthetic brine with a total salinity of 38.0 g/L and fluorinated oil as simulated oil. The initial relative permeability of rock samples varied from 0.16mD to 0.23mD, increasing to 0.19mD to 0.27mD after shut-in for various time periods. The decrease in permeability was greater at lower flow rates, and the rate of permeability recovery decreased over time. The restoration of permeability was due to aqueous phase migration from macro pores to meso pores during shut-ins, reducing water blocks near fractures and capillary discontinuity, and increasing the relative permeability of HC phase, as shown in Figure 8 (Li et al., 2019). Liang et al. (2021) investigated the impact of shut-in time on production in fractured shale formations using three core flooding samples. First, Klinkenberg permeability varied from 20.1mD to 26.2 mD but reduced by 84% to 92% after water invasion, which may be due to clay swelling, gas-water relative permeability and narrow fractures. The cores were flooded for 1 hour at 0.2 cc/min at a pressure of not more than 20 MPa and then a shut-in period of 5 hours. Higher flooding pressure led to lower flowback rates, but the impact decreased with the increase in shut-in time. The study also showed that permeability damage was caused by water invasion or particle blockage and that shut-in time did not affect it (Liang et al., 2021). Kondash et al. (2018) examined the growing use of water in hydraulic fracturing (HF) operations and the resulting increase in produced water (PW) in the US shale gas industry. Water usage and PW volume have been steadily increasing, with the Permian Basin experiencing the largest increase in water requirement (770%, from 4900 m^3 per well in 2011 to 42,500 m^3 per well in 2016). However, the Marcellus region had the least increase (around 20%, from 23,400 m^3 per well in 2011 to 27,950 m^3 per well in 2016). In terms of PW volume, the Eagle Ford region produced 1440% more wastewater from the gas-bearing section in 2015 than in 2011 (20,700 m^3 per well compared to 1340 m^3 per well) (Kondash et al., 2018). Fakhru'l-Razi et al. (2009) reviewed the harmful effects of produced water (PW) generated from shale gas systems and discussed various treatment methods. These methods were categorized into physical, chemical, biological, and membrane treatment. Examples of physical treatment methods included sand filters and cyclones, while chemical methods included chemical oxidation and photocatalytic treatment. Biological treatment involved using microorganisms to treat PW, while membrane treatment included microfiltration and reverse osmosis. The authors suggested that combining physical and membrane treatment methods could effectively treat PW, with some research achieving over 95% removal of dissolved solids and hardness (Ahmadun et al., 2009). Sonune and Ghate (2004) also emphasized the importance of effective management and treatment of PW due to its harmful effects. They concluded that more advanced treatment technologies are needed to reuse the water for various purposes. The study correlated the reuse of PW with membrane technology, which is considered the best option for recycling and reusing PW(Sonune and Ghate, 2004).

Hydraulic fracturing (HF) is essential to enhance the production of shale gas reservoirs, but challenges such as water encroachment may hinder the permeability of the formation and hence affect the production of the gas. In the recent past, Li et al. (2019) and Liang et al. (2021) have conducted studies on water invasion, permeability restoration and shut-in time. As observed by Kondash et al. (2018) the, water usage in HF has increased and therefore water management and treatment are crucial to minimize environmental effects as highlighted by Fakhru'l-Razi et al. (2009) and Sonune and Ghate (2004). Operators should adapt the shut-in techniques, create the regional water management plans, invest in advanced treatment technologies, and further research to avoid permeability damage.

Conclusion

- Conventional and unconventional reservoirs differ in porosity, permeability, HC composition, lithology, distribution, and formation mechanism. Different geo-steering techniques are needed for effective results.
- Researchers use numerical models like wire-mesh, discrete fracture model, dual-porosity model etc. to understand shale reservoir properties and production performance. Assisted history matching using neural networks and Markov chain Monte Carlo algorithm is also used.
- Heating techniques like electrical resistance and microwave heating increase cumulative gas production. Cryogenic liquid nitrogen treatment is also effective.
- Techniques like comparing shale with already producing wells, Difference-Index analogy, and modelling are used to analyse gas exploration potential in different regions.
- Increased toxic produced water from hydraulic fracturing is a concern. Advanced technologies and research are needed to address this issue for unconventional reserve exploration.

Conflict of Interest

The authors declare that there is 'no conflict of interest'.

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