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Gas Injection Transport Mechanism for Shale Oil Recovery

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***Abstract*—**The United States is now energy self-sufficient due to the production of shale oil reserves. With more than half of it being tapped daily in the United States, these unconventional reserves are massive and provide immense potential for future energy demands. Drilling horizontal wells and fracking are the primary methods for developing these reserves. Regrettably, recovery efficiency is rarely greater than 10%. Gas injection enhanced oil recovery offers a significant benefit in optimizing recovery of shale oil. This could be either through huff and puff, gas flooding, and cyclic gas injection. Methane, nitrogen, and carbon (IV) oxide, among other high-pressure gases, can be injected. Operators use Darcy's law to assess a reservoir's productive capacity, but they are unaware that the law may not apply to shale oil reserves. This is due to the fact that, unlike pressure differences alone, diffusion, concentration, and gas selection all play a role in the flow of gas injected into the wellbore. The reservoir drainage and oil sweep efficiency rates are determined by the transport method. This research evaluates the parameters that influence gas injection transport mechanism. Understanding the process could accelerate recovery by two to three times.

***Keywords*—**Enhanced oil recovery, gas injection, shale oil, transport mechanism, unconventional reservoir.

I. Introduction

UNCONVENTIONAL resources such as shale oil have benefited from advancements in oil and gas. Since 2010, shale reservoirs in the United States (US) have considerably increased oil output from productive shale plays such as the Bakken, Eagle Ford, and Permian [1], thanks to two major techniques: horizontal drilling and intense hydraulic fracturing application. They are high API crude that is trapped between layers of shale and siltstone and accounts for more than a third of US onshore production. As a result, the US have surpassed Saudi Arabia as the world leading crude oil production country. In the world's recognized shale oil reserves, Russia ranks top with an estimate of 75 MMMbbl, followed by the US with an estimate of 58 MMMbbl, according to the Energy Information Administration (EIA). China, Argentina, Brazil, Jordan, Libya, and Canada are just a few of the countries that have identified shale oil reserves. A sample of an oil-bearing shale deposit is shown in Fig. 1.

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Fig. 1 Oil-bearing shale deposit [2]

The recovery efficiency employing the major production method of horizontal drilling and multiple fracking is less than 10%. Clark et al. (2009) determined that the recovery factor for shale oil from the Bakken formation is 7% [3] based on the findings of various recovery methods. As production from the reservoir depletes, gas injection Enhanced Oil Recovery (EOR) is used, which can be done either through huff and puff, gas flooding and cyclic gas injection. During this procedure, high-pressure gas such as carbon (IV) oxide (CO_2), nitrogen (N_2), methane (CH_4), and ethane (C_2H_6) is injected into the well or formation, followed by a soaking period to allow the injected gas to displace the oil. Unlike traditional wells, this strategy fails in shale oil reservoirs because oil displacement is aided by diffusion, not pressure difference alone, as most operators believe. The movement of ions or molecules from high-concentration to low-concentration regions within a solution is known as diffusion [4]. By lowering the density of the oil, increasing the oil mobility ratio within the pores, and sweeping the oil into the wellbore, these molecules produce an imbalance within the fractures. Given the paucity of reviews in this area, this work assesses EOR methods for producing shale oil, advocates for gas injection methods, and assesses the role of diffusion, pressure difference, concentration, and gas selection.

II. Validation of Gas Injection over Other Enhanced Recovery Methods

Thermal injection, microbial injection, chemical injection, and gas injection are all potential EOR approaches. Other EOR procedures, unlike gas injection, are ineffective in developing shale oil reserves. A brief discussion of alternative EOR approaches is provided to emphasize the possibilities of employing gas injection EOR.

A. Thermal Injection Method

Flooding with hot water, steam, or in-situ combustion are all possibilities. By reducing viscosity and improving mobility ratio, this approach is particularly useful for creating reservoirs with very viscous characteristics. However, because shale oil has a viscosity of less than 1 cP, this method of EOR is ineffective for producing shale oil.

B. Microbial Injection

This method recovers oil from a reservoir by utilizing components such as microorganisms and fertilizers. They work by producing bio surfactants or bio polymers as a result of hydrocarbon digestion. Due to the creation of polymers, these approach can degrade reservoirs by closing the pores of the formation. Furthermore, the high cost of injection and development lags makes this method not often used in EOR.

C. Chemical Injection Method

Is the process of injecting dilute solution chemicals to lower surface tension and improve mobility. Surfactants, such as rhamnolipids or petroleum sulfonate, have a higher capacity for water imbibition and wettability than other chemical injection methods. The aqueous phase of the matrix may not be able to boost the oil mobility ratio due to the oil wet state of shale oil. The high cost of injecting the chemicals also put a restriction to this procedure.

D. Gas Injection Method

This is the most widely used and understood EOR approach. By lowering the interfacial tension between the oil and the water, gases like N_2, CO_2, CH_4, and C_2H_6 can be introduced to enhance oil displacement and reservoir pressure. This could happen via "huff and puff," "gas flooding," or "cyclic gas injection."

i. Huff and Puff Gas Injection

In this procedure, the gases created alongside the oil from the production well during the puff period are separated and pumped back into the well during the huff, where they are allowed to soak for a period of time. For EOR, the huff-and-puff gas injection method improves displacement efficiency and mobility ratio.

ii. Gas Flooding

Using an injection well, the separated gas from the production well is injected back into the formation. This technique has primarily been employed in traditional reservoirs as water alternating gas and simultaneous injection. Miscible flooding is the most common gas flooding mechanism in shale oil formations. This process keeps the miscibility pressure low, minimizes interfacial tension during miscibility, and boosts displacement efficiency.

iii. Cyclic Gas Injection

This mode uses both huffing and puffing as well as gas inundation at the same time. To boost the mobility ratio, the produced gas is injected back into the reservoir. It consists of three stages: injection, soaking, and production. The Big Sinking Field has been subjected to cyclic gas injection using N_2 and CO_2 to recover shale oil [5].

III. Factors that Influence Gas Injection

Following primary recovery of a shale oil reservoir, the industry practice is to boost production using EOR, mostly gas injection, which increases shale oil mobility and production efficiency. CO_2, N_2, CH_4, and C_2H_6 are all typical gases utilized in this method. After the injection of high-pressure gases, the well is closed for a period of time to allow the injected gases to absorb into the oil. However, because of the contribution of elements impacting its transport system, this strategy does not work well with shale oil reservoirs, despite the fundamental assumption that oil recovery in these very tight pores is aided by a pressure difference. The contributing elements are evaluated.

A. Pressure Difference Contribution

Using cyclic N_2 injection, Yang Yu et al. 2015 [6] studied the influence of pressure depletion rate on oil recovery from shale cores. The Eagle Ford formation provided the sample for this experiment. On the shale core, six experiments were carried out at regular intervals. The following are some of the methods employed in this study: A core plug sample from the Eagle Ford shale was dried and weighed, the plug was saturated with mineral oil, and 10 cycles of huff and puff N_2 gas injection were performed, with the recovery factor for oil and the weight of the core plug being recorded during the puff stage. The core sample was vacuumed for two days at 5 mbar, 21°C to dry the moisture content for the saturation process, which is one of the most important stages of the experiment. A displacement pump was used to pump mineral oil into the vessel until it was completely saturated. The pump outlet pressure increased dramatically as a result.

The cyclic gas injection EOR via huff and puff technique is the second critical stage. After measuring the oil saturated weight in the core, all valves were closed and the core plug was put vertically. For this experiment, the injection pressure for the huff and puff N_2 gas injection was 1000 psi. The experiment is watched until the pressure falls below atmospheric pressure, at which point the core sample is taken out and weighed.

The core sample was weighed and the recovery efficiency for each injected pressure depletion time was determined after several hours of production. The recovery efficiency increases with rising pressure and declines with increasing pressure depletion time, according to the findings.

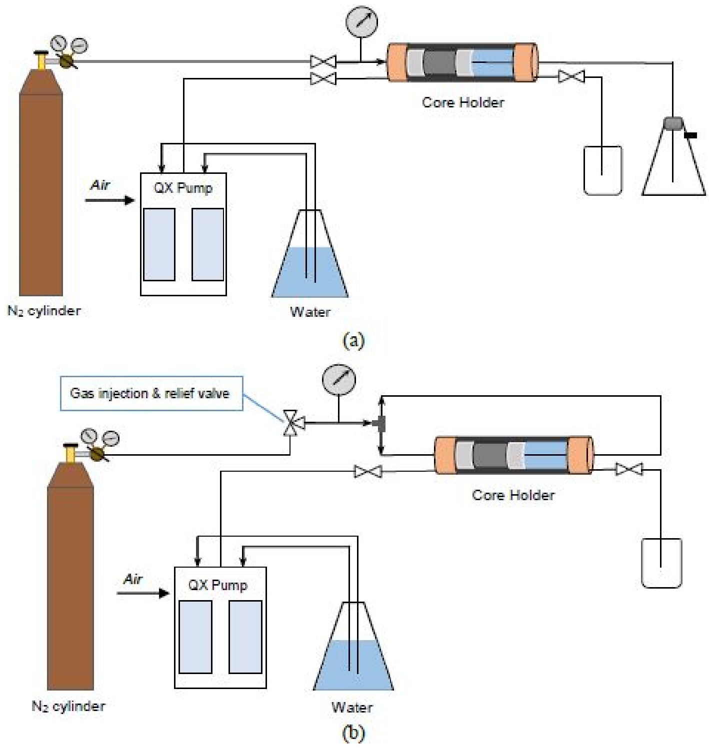

Fig. 2 Experimental setup for (a) gas flooding and (b) huff and puff gas injection [7]

B. *Diffusion's Contribution*

Diffusion's role in shale has been demonstrated in several experiments [8]-[11]. For low permeability reservoirs, diffusion is a key process. In 2013, Raghavan et al. devised a diffusion-based mass transport model for tight oil formations [12]. Dejam et al. (2017) shown that Darcy's law may predict the fluid force in a tight formation considering the relevance of pre-transport Darcy's conditions [13]. Michael Cronin et al. 2018 [14] developed a field-scale oil recovery scenario based exclusively on diffusion-dominated transport. The model has the potential to increase recovery by soaking the injected gas in the shale oil formation for a longer period of time. The model is made up of a two-dimensional matrix block with orthogonal fractures and a one-dimensional slab surrounded by a parallel fracture plane. During primary production, an analytical solution was designed to stimulate the oil in the fractures, followed by the influx of solvent into the matrix from the fracture during the huff phase and solvent with oil flux from the formation to the fracture during the puff period. The following are some crucial assumptions to consider:

- When compared to matrix transport, the conductive nature of fractures allows for rapid flow within them. As a result, the fracture pressure is set to be the same as the pressure in the bottomhole.
- Diffusion alone is responsible for mass movement in rock matrix.
- Isotropic and homogeneous matrix block.
- A single phase homogenous mixture of wellbore fluid, fracture, and matrix exists.

The results show that using a diffusion transport mechanism to reinvigorate production in a shale oil field can be done without using Darcy's law. Because the minimal miscibility pressure is limited to the advection phenomenon, it may be neglected for a diffusion focused shale oil formation. Because CH_4 and N_2 gases diffuse faster than CO_2 and require less gas to revive production, they are chosen over CO_2.

C. *Concentration Contribution*

The capacity of the injected solvent to combine with the shale oil determines how efficient the recovery process will be. The mass transfer during this phase is extremely sluggish as a result of diffusion. Enhancing frontal instability and convention at the oil interface, according to Garmeh et al. (2010), can help the oil mobility ratio [15]. This can result in viscous fingering, which can lead to a rapid gas breakthrough, reservoir drainage, and shale oil production. For miscible displacement of pore stimulation, the Concentration Dependent Diffusion Coefficient (CDDC) [16]-[17] has been used. A numerical simulator was employed by Qingwang et al. (2017) to review a concentration-dependent diffusion coefficient [18]. Using a nonlinear numerical simulator, the frontal instability was modelled at an unfavorable mobility ratio between oil and gas. This method allows for a thorough investigation of viscous fingering and interface instability. According to the findings, mass transfer efficiency and frontal instability are concentration dependent on diffusion coefficient.

D. *Gas Selection's Contribution*

Another component that influences the sweep efficiency of shale oil is gas selection. Gases like N_2, CO_2, CH_4, and C_2H_6 have been used to recover shale oil. Understanding the transport mechanism directing shale oil recovery requires an understanding of the gas injection capability for various gases. Gamadi et al. (2013) [19] used huff and puff to inject N_2 as the gas into three core plug experiments from Eagle Ford, Marcos, and Barnett shale deposits. Depending on the shale core type and injection pressure, the N_2 could boost recovery by 50%. Using huff and puff of CH_4 gas, Li et al. (2015) investigated Wolfcamp oil [20]. Their findings showed that by using a 2000 psi injection pressure and five injection cycles, oil recovery may be increased by 39%. By huffing and puffing gas infusion, Lei et al. (2017) tested the benefits of gases including CH_4, N_2, and CO_2 on core samples from the Wolfcamp formation [21]. The huff and puff experiment was carried out utilizing these three gases at a 2000 psi injection pressure after saturating the Wolfcamp core plug sample with crude oil. Oil recovery increased during the first two injection cycles and decreased as the number of injection cycles grew, according to the results of the experiment. When comparing the three gases utilized in this experiment in Wolfcamp, CO_2 result came out top, followed by N_2 and then CH_4.

IV. Conclusion

Shale oil has recently been the focus of exploration and production in the US and a large section of the world due to its large resource and advancements in research leading to its extraction. Operators use Darcy's law to evaluate a reservoir productive capabilities, however many are unaware that Darcy's law may not apply to shale oil reserves. This is because, unlike pressure difference alone, diffusion, concentration, and gas selection all play a role in the movement of gas injected into the wellbore. Furthermore, as the pressure of the injected gas is increased, the recovery of shale oil improves, but as the pressure depletion time grows, the recovery of shale oil falls. The recovery of a shale oil deposit is greatly influenced by diffusion. The density of shale oil is reduced through diffusion, allowing it to flow to the wellbore. Diffusion coefficient influences mass transfer efficiency and frontal instability. Injection gases should be chosen based on the shale formation's characteristics.

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Abbreviations

EOR – Enhanced Oil Recovery
US – United States
API – American Petroleum Institute
EIA – Energy Information Administration
N_2– Nitrogen
CO_2– Carbon (IV) Oxide
CH_4– Methane
C_2H_6– Ethane
CDDC – Concentration Dependent Diffusion Coefficient

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