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Review article

Advances in improved/enhanced oil recovery technologies for tight and shale reservoirs

Lei Wang[a,*], Ye Tian[a], Xiangyu Yu[a], Cong Wang[a], Bowen Yao[a], Shihao Wang[a], Philip H. Winterfeld[a], Xu Wang[b], Zhenzhou Yang[b], Yonghong Wang[b], Jingyuan Cui[b], Yu-Shu Wu[a]

[a] *Department of Petroleum Engineering, Colorado School of Mines, USA*
[b] *CNPC, USA*

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ABSTRACT

This paper presents a comprehensive review of the technical progress as well as updated knowledge and understandings of IOR/EOR technologies for tight oil reservoirs. Critical and in-depth assessment of various IOR/EOR methods is made upon the best practice and lessons learned, mainly, in the North America. In the past few years, many traditional and new IOR/EOR methods have been tested in laboratory and piloted in field to investigate their potential in improving oil recovery from unconventional plays, including water injection, miscible and immiscible gas injection, water-alternating-gas injection, chemical flooding, and nanotechnology. Feasibility concerns and technical challenges, such as low injectivity, formation damage, and low sweep efficiency arising from extremely low permeability and high heterogeneity in fractured tight oil reservoirs, are raised for directly adopting traditional IOR/EOR methods. IOR/EOR mechanisms in tight oil reservoirs mainly involve gas and oil flows in nanometer pores, gas dissolution and diffusion through low permeability matrix, oil swelling, wettability alteration, IFT reduction, and fracture-matrix interaction, thus thorough understanding of flow and transport mechanisms in multi-scale pores and fractures is indispensable for developing effective IOR/EOR technologies. To optimize the selection of specific gas species or chemical formulas, it is necessary to conduct preliminary assessment of practicability and viability with both experimental studies and numerical simulations for operation upscaling and production prediction before field implementation.

1. Introduction

During the past two decades, the oil and gas industry in North America has successfully evolved into the era of commercially developing unconventional oil and gas plays. As of 2015, about three quarters of the natural gas production and half of the total petroleum liquids produced in the United States were contributed by shale and tight reservoirs [26]. These numbers are predicted to keep increasing in the next few decades. Meanwhile, great success in North America enables unconventional resources to gain more and more attention in other countries, e.g., China and Argentina. Nonetheless, different from conventional oil and gas resources, unconventional resources mostly reside in low permeability rocks, where the pores are tiny and poorly connected, making it difficult for oil and gas to mobilize or flow through the rock to the well.

Shale and tight reservoirs are not newly found reserves, instead they were discovered several decades ago, but most of them were not economically recoverable until recently. In fact, in some sweet spot areas, production has been put on line not long after the discovery. For example, along some anticlines in Williston Basin, vertical wells started producing in the 1950s. Nonetheless, due to relatively low productivity, exploitation was not much expanded. In the past two decades, Williston Basin soon became one of the most commercially recoverable plays by primarily benefiting from the fast evolving technologies, i.e. horizontal drilling and hydraulic fracturing.

After hydraulic fracturing, horizontal wells drilled in unconventional reservoirs can achieve very high initial production rates of hundreds of or even thousands of barrels per day. But these wells also suffer a rapid decline in production rate during first two to three years. Based on the statistics of oil production data of wells drilled in the Permian Basin from 2007 to April 2015 [27], most of the wells drastically declined to 20% of the initial peak production rate. Fast decline in production rate engenders the well to meet the marginal cost earlier and thus forces wells to be abandoned earlier. This not only jeopardizes the return of millions of dollars invested but also leaves a huge amount of oil and gas resources in rock matrices underground.

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[*] Corresponding author.
E-mail address: lwang@mines.edu (L. Wang).

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Nomenclature

Acronyms

AS/V	apparent surface to volume ratio
bbl/d	barrels per day
cP	centipoise
CT	computer tomography
EIA	Energy Information Administration of the United States
EOR	enhanced oil recovery
EGR	enhanced gas recovery
EUR	estimated ultimate recovery
FE-SEM	field emission scanning election microscope
F&D	finding and development
gpt	gallons per thousand gallons of fluid
IFT	interfacial tension
IOR	improved oil recovery
LSCO$_2$WAG	low-salinity-alternating-CO$_2$ flooding
LTG	low tension gas flooding
Mbbl	thousand of barrels
MINC	multiple interacting continua
MMbbl	million of barrels
MMP	minimum miscibility pressure
Mscf	thousand standard cubic feet
MMscf	million standard cubic feet
mD	milli-Darcy
NDIC	North Dakota Industrial Commission
NGL	natural gas liquid
NOB	net overburden
nD	nano-Darcy
OOIP	original oil in place
STB	stock tank barrel
PN	polysilicon nanoparticles
PV	pore volume
RF	recovery factor
ROIP	remaining oil in place
SAG	surfactant alternating gas
SAGD	steam-assisted gravity drainage
SEM	scanning electron microscope
SRV	stimulated reservoir volume
USGS	United States Geological Survey
μD	micro-Darcy
VLE	vapor-liquid equilibrium
WAG	water-alternating-gas

It is known that oil and gas recovery factors (RFs) are strongly related to reservoir permeability and porosity. For conventional oil reservoirs, the RFs can generally reach 30–40% after water flooding; while for gas reservoirs, the RFs could be as high as 90%. Tella et al. [157] estimated that for tight oil reservoirs with a median porosity of 20% and permeability of μD to mD, the oil RFs could be 5–15%; and for tight gas reservoirs, RFs could be between 30% and 50%. Shale formations generally have porosity values less than 15% and permeability less than 1 mD, so their RFs would be even smaller. For oil, the RFs could be 1–10%; while shale gas RFs could vary from 5 to 30%. In comparison with conventional reservoirs, large percentage of oil and gas resources could be left in place after depletion. In view of the huge amount of the residual hydrocarbon resources and heavy investment in drilling and fracturing, it is certainly worth investigating and developing practical IOR/EOR methods in order to revitalize the unconventional plays currently under primary recovery sooner or later. With appropriate IOR/EOR technologies, relatively large incremental oil/gas production and delayed abandonments could be achieved at low cost.

2. Conventional IOR and EOR methods

Conventional IOR and EOR methods refer to the approaches that have been well developed to improve or enhance oil recovery from conventional oil reservoirs, including secondary and tertiary recovery methods. Generally, after secondary water or gas flooding (i.e. restricted IOR methods), RFs of conventional reservoirs can be elevated from about 20% to about 35–45%. Tertiary oil recovery or EOR methods refer to utilization of physics, chemistry, biotechnology to economically recover hydrocarbons from mature fields, including conformance control, chemical flooding, CO$_2$ EOR, and most current techniques adopting nanoparticles. In general, oil recovery from conventional fields can be further improved by 5–20% with tertiary EOR methods.

2.1. Water flooding

After primary recovery, water is usually injected to supplement reservoir energy and to displace remaining oil [148]. The sweep and displacement efficiencies of water flooding have been well investigated. Sweep efficiency is strongly dependent on the mobility ratio

$$M_R = \frac{\lambda_d}{\lambda_i} = \frac{K_{rd}\mu_i}{\mu_d K_{ri}} \tag{1}$$

where K_{rd} and μ_d denote the relative permeability and viscosity of the displacing fluid, while K_{ri} and μ_i denote those of the displaced fluid, respectively. Theoretically, the lower the mobility ratio is, the higher the sweep efficiency will be.

Displacement efficiency is found directly correlated to capillary number,

$$Ca = \frac{v\mu}{\sigma} \tag{2}$$

where v is the interstitial velocity, μ is the fluid dynamic viscosity, and σ is the interfacial tension (IFT). Oil recovery increases with increasing Ca. It is suggested that for oil to be mobilized, Ca should be higher than 10^{-5}. Assume that the flow velocity is 10^{-6} m/s, water viscosity is 10^{-3} Pa/s, and IFT is 25 mN/m, then Ca is 4×10^{-8}, in this case, the oil in pores are almost immobile. If a surfactant solution, e.g. petroleum sulfonates, which can reduce the IFT to 10^{-2}, is injected, then Ca could be reduced to 10^{-4}, then approximately half of the oil could be recovered [158].

At macroscale, since injected water is heavier and less viscous than reservoir oil in general, water flooding suffers from gravitational differentiation and fingering problems, resulting in early breakthrough. The heterogeneity and natural fractures of the reservoirs may further reduce the sweep efficiency by allowing water to channel through the highly permeable portion of the reservoir and forming water dominant pathways.

2.2. Gas injection

As a major EOR approach in the United States, gas injection commonly uses CO$_2$, N$_2$, or natural gas to displace oil under either immiscible or miscible condition. Compared to water flooding, gas injection could have higher displacement efficiency and can be applied to a wider range of reservoirs, especially, low permeability and heavy oil reservoirs. The main oil recovery mechanisms of immiscible gas injection are reservoir pressure supplement to drive oil towards the production wells and gas dissolution into the oil phase to make it lighter and less viscous. For a miscible process, besides the above mechanisms, IFT between injected gas and oil is dramatically reduced or even eliminated, which would significantly increase microscopic