Journal of Natural Gas Science and Engineering 33 (2016) 438–447

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Experimental and simulation study of gas diffusion effect during gas injection into naturally fractured reservoirs

Saeed Jafari Daghlian Sofla [a], Behzad Pouladi [a], Mohammad Sharifi [a, *], Babak Shabankareian [b], Mostafa Keshavarz Moraveji [c]

[a] Department of Petroleum Engineering, Amirkabir University of Technology, Tehran Polytechnic, 424 Hafez Ave, Tehran 15875-4413, Iran
[b] Islamic Azad University, Roudehen, Tehran 16555-135, Iran
[c] Department of Chemical Engineering, Amirkabir University of Technology, Tehran Polytechnic, 424 Hafez Ave, Tehran, 15875-4413, Iran

ARTICLE INFO

Article history:
Received 7 February 2016
Received in revised form
9 May 2016
Accepted 9 May 2016
Available online 12 May 2016

keywords:
Fractured reservoir
Diffusion
Low matrix permeability
Gas injection

ABSTRACT

Naturally Fractured Reservoirs (NFRs) contain a large portion of oil reserves. Most of NFRs are subjected to secondary and tertiary recovery schemes due to their low primary recovery. Gas injection into NFRs has received much attention in recent years. The main mechanisms contributing to oil recovery during gas injection into NFRs are viscous flow, gravity drainage and diffusion. The viscous flow rarely happens in NFRs due to low pressure drop and early breakthrough of injected gas in high conductive fractures. Gravity drainage is also important in fractured reservoirs with tall matrix blocks where gravity force overcomes capillary force. Diffusion is another recovery mechanism that is found to have a significant role in recovery of oil from NFRs. This has been affirmed by numerous experimental and simulation investigations in the literature. However, sole effect of this mechanism is not well recognized especially in NFRs with very low matrix permeability.

In the current work, we have experimentally studied the effect of diffusion and viscous flow on oil recovery from NFRs with tight matrix blocks. The relative importance of each mechanism which reflects the impact of convection versus diffusion is investigated. We have also studied the sole effect of diffusion on final oil recovery using two types of gas (helium and nitrogen) with different diffusion coefficients. Results show that effect of diffusion in tight reservoirs is significant and comparable to effect of viscous flow. Numerical simulation also was conducted to verify results obtained in four experiments involving nitrogen injection. Simulation results reveal that current models for diffusion do not take into account the role of diffusion in ultimate oil recovery properly.

1. Introduction

Naturally Fractured Reservoirs (NFRs) extensively contribute to supply of today's energy demand. Reports show that they comprise about forty percent of world oil reservoirs (Saidi, 1983; Firoozabadi, 2000). Behavior of NFRs is different from those of conventional reservoir due to presence of two different media: matrix and fracture. In most cases, matrix blocks acts as the hydrocarbon storage capacity while fluid flow path is primarily provided by interconnected fractures. In a review on recovery factor of fractured reservoirs by Allan and Sun (2003), he declared poor recovery factor of naturally fractured when compared to many conventional reservoirs. High permeability contrast between the fracture and matrix often lead to low primary recovery from these reservoirs compared to conventional reservoirs (non-fractured). In fractured reservoirs because of high conductivity of fracture and low permeability of matrix, early oil production mainly occurs from fractures and matrix blocks can remain almost intact and fully saturated with oil. In other word, oil has been trapped by water or gas. In many cases in gas invaded or water invaded zone or in injection process, fractures are filled with water or gas while matrix blocks are saturated with oil. Gas injection has received much attention as a remedy to low primary recovery factor in NFRs and especially in oil wetted systems (van Golf-Racht, 1982). Gas injection assists recovering of considerable quantities of matrix-trapped oil. Hoteit and Firoozabadi (2009) state that gravity drainage,

* Corresponding author.
E-mail addresses: s_jafari@aut.ac.ir (S.J.D. Sofla), behzad.pouladi@aut.ac.ir (B. Pouladi), m_sharifi@aut.ac.ir (M. Sharifi), babak.sh.kareian@Gmail.com (B. Shabankareian), moraveji@aut.ac.ir (M.K. Moraveji).

http://dx.doi.org/10.1016/j.jngse.2016.05.035
1875-5100/

physical diffusion, viscous forces, capillary forces, total pore compressibility and phase behavior effect are main mechanisms playing role in oil recovery from fractured reservoirs subjected to gas injection schemes. Rock and fluid properties such as reservoir geology and PVT specify dominating recovery mechanism. Many authors have suggested gravity drainage as one of the main recovery mechanisms in NFRs subjected to gas injection (Zendehboudi et al., 2011). However, in cases of low permeability matrix, thin matrix blocks or trivial density difference between the oil and the injected gas, gravity drainage becomes ineffective and diffusion becomes the dominant recovery mechanism (Kahrobaei et al., 2012; Kazemi and Jamialahmadi, 2009). In this case, diffusion will take place between the gas in the fracture and the oil in the matrix (Morel et al., 1993). The components of injected gas diffuse from the fracture system into the matrix and components of the oil diffuse toward the fracture system. This results in an oil production (Yanze and Clemens, 2012). Parameters governing fluid exchange between matrix and fracture by molecular diffusion mechanism are matrix block size, fracture intensity and values of components diffusivity coefficients (Hoteit and Firoozabadi, 2006). In the case of tall matrix block, low interfacial tensions and large density difference between the oil inside the matrix and the injected gas, gravity drainage can dominate diffusion effect (Le Gallo et al., 1997; Farzaneh et al., 2010). Phase behavior mechanism is more noticeable at high pressures (Hoteit and Firoozabadi, 2009).

Recent experimental and simulation investigation reveals that diffusion can remarkably enhance the oil recovery in NFRs. Hoteit and Firoozabadi (2009) declare substantial oil recovery due to diffusion mechanism in NFRs unlike the non-fractured porous media. This happens thanks to greater gas/oil contact in NFRs and direction non-uniformity of diffusion and convective flow in NFRs unlike the non-fractured porous media. However, role of diffusion on recovery of oil in NFRs especially those with low permeability matrix is not well recognized. This invokes further experimental and simulation study to be implemented.

Several simulation studies have been conducted to evaluate diffusion effect in oil recovery from NFRs. The results show that the effect of diffusion can increase cumulative oil production up to 25% compared with a case neglecting the effect of diffusion (Yanze and Clemens, 2012). Da Silva and Belery (1989) conducted numerical simulation to assess the effect of diffusion in highly fractured with low permeability matrix in North Sea. The reservoir was subjected to early dry gas injection. In that study, they considered replacing nitrogen with dry gas. They concluded that activating diffusion mechanism leads to less depletion due to reservoir pressurizing, reducing interfacial tension and oil viscosity. Saidi (1996) understood the importance of diffusion during history matching of the Haft-Kel reservoir. The reported permeability range in this study was 0.05–0.8 md. He then used all available data to develop a numerical simulation model to predict the reservoir performance during produced gas reinjection. He found the field re-pressurizing by gas injection as the most efficient secondary recovery in Iranian fractured limestone reservoirs. Hoteit and Firoozabadi (2006) simulated gas injection using finite element method. They presented four examples in which they used methane, carbon dioxide and dry gas as the injected gas. The permeability range in their examples varied from 0.1 to 10 md. Their simulation results showed 25% increase in oil recovery by including diffusion with their method relative to the case without diffusion. Alavian and Whitson (2010) simulated the effect of diffusion on oil recovery by miscible CO_2 injection at reservoir conditions. They studied effect of different parameters such as matrix block dimension, permeability, reservoir pressure and injection rate. They concluded that molecular diffusion has a significant effect on oil recovery. They reported that oil recovery in Haft Kel reservoir increases from 22% to 78% by considering diffusion effect. Reservoir pressure, matrix permeability and dimension does not affect ultimate recovery but rate of recovery increases by increasing matrix permeability and decreasing matrix dimension. Trivedi and Babadagli (2009) presented a combined laboratory scale experimental and numerical approach to address mass transfer between matrix and fracture including effective diffusion and dispersion in the matrix of NFRs. They found that various parameters such as injection flow rate, matrix-fracture length, matrix porosity and permeability affect solvent diffusion from matrix into the adjacent fracture media. They also concluded that mass transfer rate was linearly dependent on solute velocity in the fracture. Shojaei and Jessen (2015) simulated diffusion effect in a dual-porosity model in which generalized Fick's law was used for molecular diffusion. They compared their model with conventional models using several field-scale examples with different values of key parameters such as matrix permeability, fracture spacing and reservoir pressure. It was demonstrated that the dragging effects (off-diagonal diffusion coefficients) can significantly impact the oil recovery during gas injection in fractured reservoirs. Off-diagonal diffusion coefficient also known as cross-diffusion coefficient is a coefficient used to account for diffusion flux of a component induced by existence of another component gradient.

Molecular diffusion has been introduced as an efficient recovery mechanism based on several experimental and field observations (Kahrobaei et al., 2012). Al-Bahlani and Babadagli (2012) visually investigated the interaction of fluids in the fracture and matrix imitating solvent injection into NFRs using Hele-Shew model subjected to different boundary conditions. They concluded that under a fully static condition between solvent and oil, the process is mainly governed by boundary conditions and relative contribution of gravity and diffusion to the interaction process. Few number of works has investigated diffusion coefficient of gases mainly N_2, CO_2 and C_1 in the oil phase (Chukwuma, 1983; Renner, 1988; Riazi et al., 1994). The pressure decay method proposed by Riazi et al. (1994) has received much interest owing to its simplicity and robustness. In the most experimental investigations, fracture is simulated by creating a gap between the core and core holder or artificially fracturing rocks. Employing aforementioned approach, authors have experimentally investigated effect of CO_2 diffusion on oil recovery (Darvish et al., 2006; Lie, 2013). Lie (2013) studied effect of CO_2 diffusion on oil recovery in artificially fractured chalk rocks. He used CT scan images and nuclear tracer in the CO_2 phase to analyze CO_2 saturation distribution during experiments. The results show in the tight shale cores with nano-darcies permeability and highly conductive fracture, recovery of oil is dominated by molecular diffusion. Ren et al. (2015) presented a systematic evaluation of CO_2 flooding in tight oil reservoirs. They studied miscible and near-miscible CO_2 into a tight reservoir in china. They found that near miscible CO_2 injection is more efficient compared to miscible flooding specially in tight oil formations. They also concluded that fractures and heterogeneities can cause miscibility instability. Darvish et al. (2006) investigated CO_2 diffusion effect on oil recovery from low permeable matrix at reservoir conditions. They used a chalk outcrop with permeability of 4 md analogous to North Sea reservoir rock. They studied the component exchange between the oil in the matrix and CO_2 in the fracture by analyzing the produced fluids. They showed in both simulation and experimental results, diffusion has considerable effect on oil recovery. On the other hand, they demonstrated that in the tight matrix block, gravity drainage does not have any significant effect on oil recovery. They suggested that the available compositional simulators should be modified to obtain better match between experiments and simulation. Karimaie et al. (2007) performed experiments to address simultaneous effect of gravity drainage and diffusion using N_2 and CO_2 diffusion in oil-wet reservoirs. They used a low