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Contribution of osmotic transport on oil recovery from rock matrix in unconventional reservoirs

Binh T. Bui *, Azra N. Tutuncu

Unconventional Natural Gas and Oil Institute, Colorado School of Mines, 1500 Illinois St, Golden, CO 80401, USA

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ABSTRACT

The fluid transport mechanisms in fracture and rock matrix play a critical role in economic viability of hydrocarbon recovery from unconventional reservoirs. Several transport mechanisms, including advection, diffusion, and convection, have varying degrees of contribution to hydrocarbon recovery depending on the transport properties of the formation. The contribution of the concentration gradient driven diffusion, or osmotic transport on hydrocarbon recovery has been numerically investigated in this study. The main objective of this study is to determine when the osmotic transport plays an important role on the mass exchange between the fractures and the rock matrix.

In this study, a model for the mass transport between the rock matrix and the fractures has been formulated and validated with the experimental data. The numerical results showed that osmosis is an important force imbibing water into low permeability rock matrix and enhancing the effectiveness of low salinity waterflooding on oil recovery. The imbibition of water into oil-wetted shale matrix is mainly driven by the osmotic transport and wettability alteration. The contribution of the osmotic transport on oil recovery continues a long period of time, typically in a few years. This contribution increases if the membrane efficiency is high and the matrix block size is small. However, shale membrane efficiency is typically less than 10% considerably reducing the oil recovery factor by osmosis to less than 5%. Higher membrane efficiency and lower diffusion coefficient of dissolved ions increase the contribution of osmosis on the oil recovery from shale matrix.

1. Introduction

Unconventional reservoirs require unconventional techniques to produce economically. Shale matrix is often characterized by very low permeability, typically in nano-Darcy (*nD*) scale. To economically produce from this type of reservoirs, fracture-stimulation is widely used. During the hydraulic fracturing operation, fracturing fluid is pumped at high pressure into the formation to generate the hydraulic fractures. A portion of this fluid imbibes into the shale matrix and a portion returns to the surface through the wellbore after the fracturing. The fluid recovered during the clean-up phase is called flow-back fluid or flow-back water. The volume of water flow back is often less than the injected volume. The reason for this low water flow-back is still not very well understood. Some researchers suggest that this water may be trapped in secondary fractures or imbibe into the rock matrix (Blauch et al., 2009; Ghanbari et al., 2013; Haluszczak et al., 2013). The field data and experiments conducted by Ghanbari et al. (2013) show that the salinity of flow-back water increases with time. This could be the result of the solute exchange between the fractures and the shale matrix. The longer the water contact with the shale matrix, the more solutes mitigate out of the matrix increasing the flow back water salinity (Bui, 2016).

With the presence of natural and hydraulic fractures, dual-porosity model is often used to idealize the behavior of unconventional reservoirs at the reservoir scale. The flow of the fluid in the fracture is the dominating flow in the reservoir. While traveling along the fractures, mass exchange takes place with the adjacent matrix blocks. The mechanism of this mass exchange depends on the flow properties and geometry of the matrix block. The common approach to model the mass transport between the fractures and the rock matrix is through the mass transfer functions. In the early work of fractured reservoir modeling, only pressure gradient was considered as the driving force for this mass exchange (Warren and Root, 1963). The importance of accurate calculation of the mass transfer between the fractures and the rock matrix is detailed by Ramirez et al. (2009) and Al-Kobaisi et al. (2009). This mass exchange determines the ultimate recovery from the reservoir. In addition to the hydrocarbon recovery, the accuracy of calculating this mass exchange is

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* Corresponding author.
E-mail address: binh-bui@utulsa.edu (B.T. Bui).

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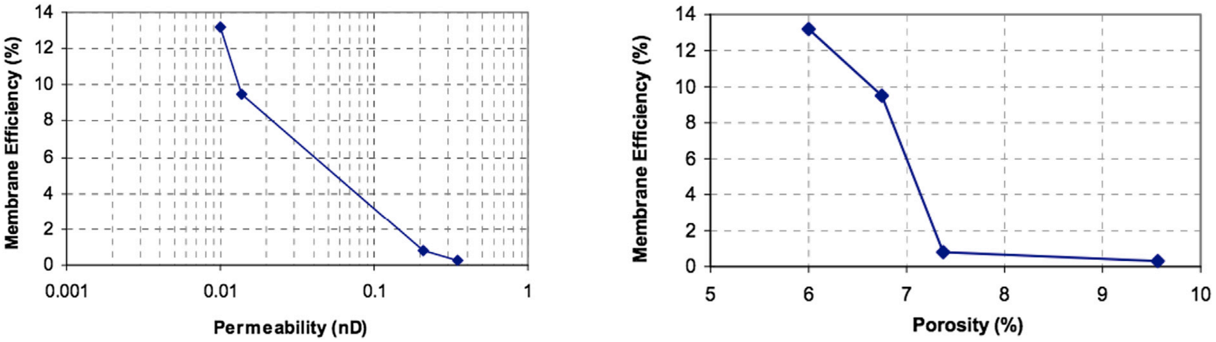


Fig. 1. Measured membrane efficiency of Atoka Shale as a function of matrix permeability and porosity (Osuji et al. (2008)).

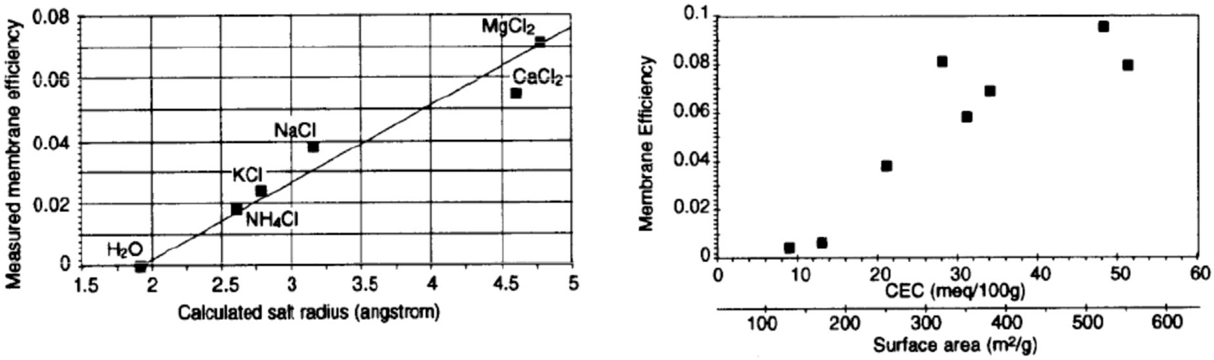
important for modeling the complexity of the reservoir at different scales in unconventional reservoirs. Hence, understanding the mechanism governing this mass exchange has been one of the focus areas of the current researches toward the improved and enhanced hydrocarbon recovery, especially for unconventional reservoirs (Bui, 2016).

The transport processes between fluid in the fractures and the rock matrix include advection, molecular, thermal and electrochemical diffusions, and thermal convection. In conventional fractured reservoir modeling, analytical transfer functions are quite sufficient to evaluate the mass transfer between the rock matrix and the fractures. The transfer function is mainly considered advective transport that is described by Darcy's Law. However, for shale formations, low permeability decreases the effect of convection. Molecular and electrochemical diffusions and mechanical dispersion are more important (Farrokhrouz and Asef, 2013; Ozkan et al., 2010). Since diffusion and thermal convections are very slow processes, these mass transport processes are strongly time dependent. The longer injected fluid stays in contact with the rock matrix, the more the fluid imbibes into the rock matrix expelling oil out of the matrix. This may explain why shutting-in the well or re-fracturing often increases the production.

The recovery from unconventional reservoir is often very small, typically less than 10%, most often in the range from 3 to 7% EIA (2013). Research on the improved and enhanced hydrocarbon recovery from these tight formations is currently focusing on the mechanism of the mass exchange between the fractures and the rock matrix. One area of active research is low salinity waterflooding. This new technology is recently received a significant attention from research community as a method to improve the mass exchange between the fractures and the rock matrix, hence improving the hydrocarbon recovery. The improved recovery due to the low salinity water injection has been attributed to the decrease of ion binding (Lager et al., 2007), the alternation of wettability from non-water-wet towards more water-wet (Ligthelem et al., 2009), and the change of the relative permeability and capillary pressure curves (Masalmeh et al., 2014). The variation of the pH has also been considered as a mechanism for the increase of recovery (Austad et al., 2010; Rezaeidoust et al., 2010). One important transport mechanism receiving much attention recently is the imbibition of low salinity water into rock due to osmotic pressure. The osmotic pressure can be an additional force that improves the hydrocarbon recovery. The difference in salinity between fracturing fluid and formation brine creates the concentration gradient and osmotic pressure. This osmotic pressure induces the flow of water from fractures into the matrix pores containing high-salinity concentration.

Osmotic pressure is the pressure applied by a solution to prevent the inward flow of water across a semipermeable membrane. Osmosis is the process in which a liquid passes through a membrane which allows the passage of solvent molecules but is too small for the larger solute molecules to pass through. Because the molecules are in random motion, there will be more molecules moving from the high concentration region to the low concentration region. The motion of a substance from a high concentration region to a low concentration region is called diffusion. In the absence of a hydraulic pressure gradient, the movement of fluid into shale matrix is mainly governed by the chemical potential difference between the pore fluid and the injected fluid. This results in the osmotic transport of water into rock matrix (Ewy and Stankovich, 2000). The osmotic potential generated between shale matrix and fluid in the fractures is greatly influenced by the flow of ions into or out of shale matrix caused by the ionic concentration imbalances. Therefore, the actual osmotic effect is often less than the osmotic potential. The determination of the impact of ionic flow on the osmotic potential initiates the concept of shale membrane efficiency (Osuji et al., 2008).

The transport of the solute in shale depends strongly on the membrane properties of the shale matrix. The membrane efficiency or modified diffusion potential is used to describe the ability of the membrane to prevent solute transport. Membrane efficiency is the measure of how well a membrane can prevent ion movement. In the absence of the



(a) Membrane efficiency versus calculated salt radius.

(b) Membrane efficiency versus CEC/surface area.

Fig. 2. Membrane efficiency versus calculated salt radius and CEC/surface area for Pierre type I shale exposed to chloride salt solutions at a water activity of 0.76 (van Oort et al., 1995).