Journal of Petroleum Science and Engineering 122 (2014) 18–30

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Performance assessment of miscible and immiscible water-alternating gas floods with simple tools

R. Laochamroonvorapongse [a,1], C.S. Kabir [b,*], Larry W. Lake [c]

[a] UT-Austin, United States
[b] Hess Corporation, United States
[c] Department of Petroleum & Geosystems Engineering, U. of Texas at Austin, 200 E. Dean Keeton St., Austin, Texas 78712, United States

ARTICLE INFO

Article history:
Received 12 July 2013
Accepted 9 August 2014
Available online 1 September 2014

Keywords:
water-alternating gas floods
capacitance-resistance modeling
applications of analytical tools

ABSTRACT

Water-alternating-gas (WAG) floods are designed to lessen the mobility of CO_2 and thereby increase sweep efficiency. Common factors that often lead to less-than-ideal flood performance include reservoir heterogeneity triggering nonintuitive injector/producer connectivity, lack of conformance control, and injection at pressure greater than the fracture pressure, among others. Therefore, intensive reservoir monitoring and data interpretation should be the cornerstone of any prudent reservoir-management practice.

This study uses a slate of analytical tools to monitor flood performance in miscible and immiscible WAG floods. These tools include the capacitance-resistance model (CRM) and several diagnostic plots, such as the reciprocal-productivity index (RPI), the water–oil ratio (WOR), EOR-efficiency-measure plot, and modified Hall plot (MH). This paper offers several alternative CRM solutions to account for unbalanced patterns.

1. Introduction

Field studies demonstrate the success of miscible and immiscible WAG processes (Koottungal (2012)). Christensen et al. (2001), citing 59 field cases gathered from worldwide operations, concluded that the improved recovery occurred ranging from 5% to 10% of original oil in place. Loss of water injectivity and corrosion in injection and production systems were the only negative aspects associated with any CO_2 WAG. A subsequent study by Manrique et al. (2007) of 61 reservoirs in the United States suggested that injection of gas or CO_2 is ideally suited because of inherently small-injectivity into carbonate reservoirs and an abundance of low-cost CO_2.

Injection of CO_2 is also the logical first step toward its geologic sequestration. In fact, in recent studies, de Kok and Clemens (2009), Ettehadtavakkol (2013), and Sobers et al. (2013) explored the coupled nature of oil recovery and CO_2 sequestration question in an offshore field in Trinidad and in the Vienna basin, respectively.

Giordano et al. (1998) proposed a rapid method for forecasting the performance of miscible WAG (MWAG) and immiscible WAG (IWAG) at the field scale with streamline simulations. Such simulations are much faster than their finite-difference counterpart. Asghari et al. (2007) proposed field-specific practical correlations for rapid assessments of CO_2 flood performance in the Weyburn field in Canada.

Several publications exist that promote reservoir management of primary and waterflood operations with surveillance data. Some of the papers that examine the application of CRM include Izgec and Kabir (2012) for primary oil production and Izgec and Kabir (2010), Kabir and Boundy (2011), Nguyen et al. (2011), Kaviani et al. (2012), Parekh and Kabir (2013), Sayarpour et al. (2009a), and Weber et al. (2009) for waterfloods. Although many authors have reported laboratory and flow-simulation studies for specific fields, there are few reporting on the use of surveillance data in learning various nuances of ongoing WAG.

This study attempts to fill this perceived gap in the WAG flood operations for two cases. The first case is a MWAG process in a carbonate reservoir, and the second case is an IWAG in a turbidite, sandstone reservoir. Injection of single-phase fluid, such as pure CO_2 in MWAG and water in IWAG preceded the WAG period. Periodic injection logs provided insights into the MWAG process, whereas interwell tracer surveys provided some clues about well connectivity in the IWAG operation.

* Corresponding author at: Hess Corporation, 1501 McKinney Street, Houston, Texas 77010, United States.
[1] Current address: PTT Exploration and Production Public Company Limited, 555-1 Energy Complex Building A Vibhavadi-Rangsit Rd. Chatuchak, Bangkok, Thailand 10900.

http://dx.doi.org/10.1016/j.petrol.2014.08.012
0920-4105/

2. Analysis methods

This study presents a slate of analytical tools that are applied to learn about the reservoir behavior en route to understanding injector/producer connectivity, leading to the assessment of a matured and an evolving WAG flood. In this context, CRM is an important analytical tool that can help understand reservoir performance of any flood regardless of its maturity.

Production and injection data are necessary for the analysis, although availability of flowing bottomhole pressure enhances the analysis. Basically, CRM (Sayarpour et al. 2009a, 2009b) is based on material-balance and signal analysis, which allows establishing connectivity or lack thereof between the injector/producer pairs. The CRM expression was derived from the continuity equation with the assumptions of stable flow, unchanged number of producers, constant compressibility and productivity index, and no aquifer. The following CRM equation by Sayarpour et al. (2009a and 2009b) is used here.

$$q_j(t_k) = q_j(t_{k-1})e^{-(\Delta t_k/\tau_j)} + (1 - e^{-(\Delta t_k/\tau_j)})\left(\sum_{i=1}^{n_i} f_{ij} i_i^k - J_j \tau_j \frac{\Delta p_{wf,j}^k}{\Delta t_k}\right) \quad (1)$$

The CRM inputs are production and injection rates and flowing bottomhole pressure data. With the objective function to minimize squared rate error, the following outputs can be obtained from non-linear multivariate regression: fraction of injection f_{ij} signifying injector/producer connectivity, well productivity index J_j, and pore volume related to each producer $V_{p,j}$. In post-breakthrough situations, injected water acts as a tracer; streamline simulations corroborated these findings, as reported by Izgec and Kabir (2010).

Some of the other diagnostic tools aiding our understanding of flood performance are reciprocal-productivity-index or RPI (Kumar, 1977), water–oil ratio or WOR (Yortsos et al., 1999), and modified-Hall (Izgec and Kabir, 2009) plots. The RPI response suggests the degree of pressure support observed at a given producer, regardless of the source. For instance, a zero slope on the RPI versus time plot implies one-to-one voidage replacement, whereas an increasing positive slope suggests progressively smaller pressure support. Over replacement of voidage causes a negative slope. When used in combination with CRM, the RPIs of various producers provide corroboration of the flood's response.

Whereas the RPI plot suggests pressure support, the WOR and GOR responses indicate fluid displacement around a producer. For instance, a steep slope occurring immediately after breakthrough on the log-log graph of WOR or GOR versus time suggests highly efficient displacement for either gas (the GOR) or water (WOR). In contrast, a unit-slope response indicates channeling through a high-conductivity region (thief zones or fractures), suggesting poor volumetric sweep efficiency.

EOR-efficiency-measure plot by Panda et al. (2011) enables us to compare the flood efficiency across patterns and assets. The EOR efficiency, ratio of cumulative miscible gas injected and EOR oil produced, is plotted against returned miscible gas injected (RMI). The larger RMI and smaller-than-expected EOR efficiency indicates inefficient flood performance and/or presence of thief zone.

The use of the modified-Hall plot can illuminate significant changes in mobility in WAG injection. Ordinarily, when the Hall-integral-derivative (HID) response overlays on the Hall-integral (HI) curve, injection into a matrix is occurring. In contrast, when the HID is above the HI curve, plugging is suggested and HID below the HI curve implies fracturing. Typically, when water injection follows gas injection, severe flow impediment occurs.

3. Case studies

This section discusses two case studies. The first is of CO_2 MWAG injection, following pure CO_2 injection. The second study is an IWAG, where reinjected solution gas is used for conformance improvement.

To understand both WAG performances, a set of analytical tools were used, such as CRM (Sayarpour et al., 2009b), the reciprocal productivity index or RPI (Kumar, 1977), and log WOR (Yortsos et al., 1999) and log GOR (Kabir and Young, 2004) plots. Two techniques for handling the mass imbalance in the CRM are explored in the MWAG case. Methods for improving the CRM solution are shown in both cases.

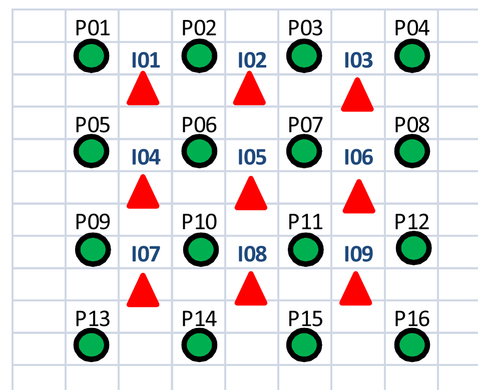

Fig. 1. Schematic of vertical well locations in the carbonate field. Prefixes P and I are producers and injectors, respectively.

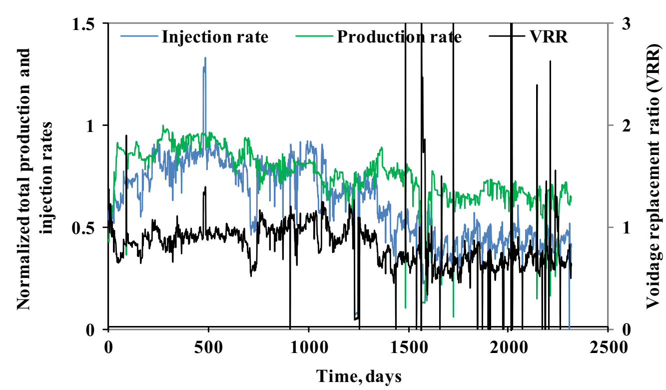

Fig. 2. Normalized total field production and injection rates, and voidage replacement ratio (VRR).

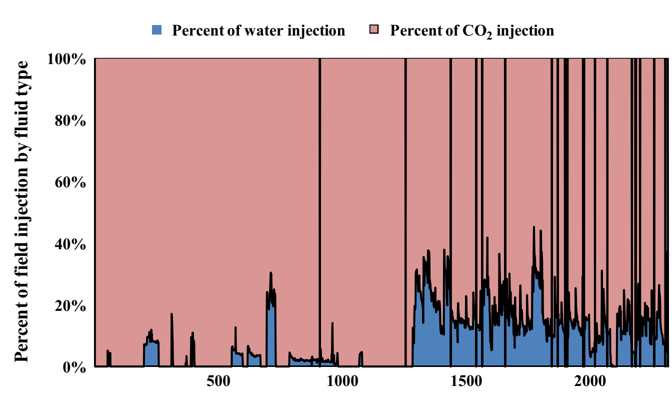

Fig. 3. Percent of field injection rates in RB/D by fluid type in miscible WAG.