Journal of Petroleum Science and Engineering 102 (2013) 1–9

Contents lists available at SciVerse ScienceDirect

Journal of Petroleum Science and Engineering

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

A case study of improved understanding of reservoir connectivity in an evolving waterflood with surveillance data

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ARTICLE INFO

Article history:
Received 16 December 2011
Accepted 14 January 2013
Available online 29 January 2013

Keywords:
waterflood surveillance and modeling
capacitance–resistance modeling
tracer testing
rate-transient analysis
Modified-Hall analysis
material-balance analysis

ABSTRACT

Establishing connectivity among various injectors and producers is a key to improve the understanding of a reservoir under waterflood. This understanding improves the estimates for ultimate recovery and also helps to better define the future development plan. In deepwater turbidite reservoirs, numerical flow-simulation models are used to make performance predictions, with reservoir connectivity as one of the key uncertainties.

In the initial phase of field development, interwell tracers were used to assess the connectivity. As more wells were drilled, updates were required for the simulation models. Instead of waiting for the next phase of an ongoing tracer program, both rate-transient analysis (RTA) and capacitance–resistance model (CRM) were used to understand connectivity. The input for both RTA and CRM are the rates and pressures, which are being gathered with real-time surveillance.

This paper presents a case study to compare findings from the use of interwell tracer data with the results of CRM based on dynamic data. Another study element demonstrates the use of RTA in identifying and estimating the volume of thief zone. Attempts are made to use CRM and RTA to predict connectivity based on performance prior to experiencing water breakthrough.

These case studies demonstrate the application of RTA and CRM in ongoing waterfloods. The CRM concurred with the initial tracer results and helped to understand the change in pressure distribution with time as the field was being developed. We learned that the use of CRM can be a viable alternative to an interwell tracer program to reduce uncertainty related to injector–producer connectivity. CRM also helped in understanding the efficiency of the injectors, which is important in a facility with limited water injection capacity. The ease of use of CRM and RTA makes them useful as screening tools in the process of developing a detailed flow-simulation model.

1. Introduction

Monitoring changing permeability and skin with time using permanent downhole sensors have been reported by many authors. Studies of Haddad et al. (2004), Coludrovich et al. (2004), and Weiland and Azari (2008) are cases in point. Horne (2007) summarized many of the technical benefits of surveillance in his seminal work. Studies providing operational guidance from surveillance and implementation of the notion of digital oilfield are many; those of Shyeh et al. (2008) and Maskeri et al. (2008) are worthy of note.

Over the last decade, the use of real-time surveillance data for frequent updates of a grid-based model has gained considerable momentum. Studies of King et al. (2002), Chacon et al. (2007), Langaas et al. (2007), Hustedt and Snippe (2008), and Panda et al. (2009), and over the last decade show the obvious benefits of integrating surveillance data with full-field simulation studies.

Most of the studies cited above are limited to the use of snapshots of dynamic data, such as pressure-buildup analysis and production-log analysis, rather than trying to understand the evolving nature of the flood with dynamic analytical tools complementing numerical modeling over long, contiguous time spans. More recently, Kabir and Boundy (2011) showed benefits of integrating various analytical tools to understand the nuances of reservoir behavior during history matching with a grid-based model. The use of rate transients often provides important clues about a reservoir's performance. In fact, the notion of reservoir management can revolve around many elements of rate-transient analysis (RTA), as discussed by Kabir and Ismadi (2011), among others. Fundamentally speaking, the RTA (Palacio and Blasingame, 1993) estimates the connected pore-volume associated with a producer. In a multiwall system, either expansion of the drainage volume owing to a prolonged shut-in of a neighboring well or drilling of a new producer or injector may cause the change in

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http://dx.doi.org/10.1016/j.petrol.2013.01.004

Nomenclature

c_t	total compressibility, 1/psi
e_w	out-of-pattern production support, RB/D
f_{ij}	fraction of injected water, dimensionless
$I(t)$	injection rate, RB/D
J	productivity index of producer, RB/D/psi
k	permeability, md
p	pressure, psi
p_i	initial reservoir or aquifer pressure, psi
p_{wf}	flowing bottomhole pressure of producer, psi
Δp	pressure difference between reservoir and aquifer, psi
$q(t)$	total production rate, RB/D
t	time, days
t_D	dimensionless time (define)
V_p	drainage pore volume of reservoir, ft^3
ϕ	reservoir porosity
τ	time constant, days

Subscripts

j	producing-well index
n	current timestep
p	pore (volume)
t	total (compressibility)
wf	wellbore flowing

pore volume owing to interference. Recently, Ismadi et al. (2012) showed the changing connected pore-volume associated with a producer because of prolonged operational shut-in of a nearby well.

An important analytical tool that can help to understand reservoir performance of an evolving flood is the capacitance–resistance model (CRM). Based on the material-balance principle and signal analysis, CRM (Yousef et al., 2006 ;Sayarpour et al., 2009a, 2009b; Kaviani et al., 2012) allows ascertaining connectivity or lack thereof amongst injector/producer pairs. In this respect, CRM is truly a multiwall pulse-test analysis tool that exploits fluctuating injection signals propagating toward producers. Therefore, both the real-time rate and pressure data recorded at all producers are important factors for analysis to ensure results with a high degree of confidence. This method′s appeal stems from the fact that no additional expenses are required for testing because the rate information provides the necessary ingredients even before the injectant breakthrough occurs at the producers, as shown by Izgec and Kabir (2010). In the post-breakthrough situation, injection water may be construed as a tracer response; streamline simulations corroborated all the findings of that study. Earlier, Sayarpour et al. (2009a) presented the underlying formulations of the CRM and also showed their applications (2009b) in the field, among others. In other words, the CRM provides an ideal opportunity for understanding reservoir connectivity at the inception of a flood.

This study presents a slate of analytical tools that are applied to learn about the reservoir behavior en route to understanding injector/producer connectivity. In particular, the CRM results are compared with those of a tracer test for a fault block to shed light on injector/producer connectivity. This learning, in turn, is expected to assist improved management of an ongoing waterflood in a well-instrumented field. Some of the other diagnostic tools aiding our understanding include reciprocal-productivity-index or RPI (Kumar, 1977), water–oil ratio or WOR (Yortsos et al., 1999), and modified-Hall (Izgec and Kabir, 2009) plots.

2. Case studies

The case studies presented in this paper are based on a field in West Africa. This field has multiple reservoirs under waterflood. All producers have downhole and wellhead pressure sensors together with frequent rate metering as part of the real-time monitoring strategy, leading to intervention as needed. Each reservoir has multiple stacked sands, often with commingled production and injection. Naturally, questions arise about production/injection allocation in each layer and inter-reservoir connectivity. Consequently, this reality adds complexity in understanding the degree of connectivity between various injector/producer pairs. To address this uncertainty, an interwell-tracer program was initiated in August 2008. Thus far, tracers have shown up at some of the producers and have provided qualitative information about connectivity. However, water has not broken through as yet in up-dip producers, thereby clouding the connectivity question for those producers.

The need for model update surfaced with drilling of additional wells in 2010. Given the time it has taken for the initial tracer program to reveal itself in some of the reservoirs, we explored other techniques to improve understanding of reservoir connectivity. For this purpose, tools such as CRM and RTA were used. Effort was made to compare CRM findings and the information gathered from the existing tracer program, such as in Case 1, where intra-reservoir connectivity was sought. In Case 2, we explored the inter-reservoir connectivity question amongst four geobodies, where no tracer program was implemented. Finally, Case 3 discusses a scenario where the presence of a thief zone was confirmed by CRM and RTA, aided by 4D seismic and injector analysis with the modified-Hall method (Izgec and Kabir, 2009).

The input for both CRM and RTA are the rates and bottomhole pressures, which are being gathered with real-time surveillance. Other appropriate analytical tools along with tracer data were brought to bear to obtain clarity in the flood′s performance to date. Table 1 is a summary of tools used in different cases.

2.1. Case 1: understanding intra-reservoir connectivity

EN is one of the reservoirs under waterflood in the field of study. This reservoir initially had one producer, P-1, and one injector, I-1. The P-2 producer was added about 1150 days after the project′s initiation. As part of the interwell tracer program in the field, a chemical tracer was injected into I-1 well to ensure that this reservoir was isolated from a different nearby waterflooded reservoir. The tracer was injected into I-1 well after 12 months from the inception of injection. Prior to P-2 well′s

Table 1
Summary of tools used in various case studies.

Analytical tools	Case Study-1	Case Study-2	Case Study-3
Capacitance–resistance model	×	×	×
Rate-transient analysis			×
Water–oil ratio			×
Reciprocal-productivity index		×	
Material balance	×		
Modified-Hall plot			×