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Interwell connectivity evaluation in cases of changing skin and frequent production interruptions

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ABSTRACT

Evaluating interwell connectivities can provide important information for reservoir management by identifying flow conduits, barriers, and injection imbalances. Injection and production rates, in ideal conditions, contain connectivity information. A number of methods have been proposed to predict connectivity based on these data. Unfortunately, many of these rate based methods have not proven to be as successful as intended because of factors external to the reservoir. Field maintenance procedures, such as shut-ins and work-overs, cause production rate changes which are not caused by injection rate fluctuations but which mislead connectivity estimators. We have developed a method which is tolerant to changes caused by external factors.

This method, called the Multiwell Compensated Capacitance Model (MCCM), is based on the superposition principle. It can analyze injection and production data when producers' skin factors change, new producers are added, or active producers are shut-in. The MCCM also deals with another common problem in field data, which is when there are frequent producer shut-ins within sampling intervals (mini-shut-ins). For example, a producer is shut-in for a few days when flow rates are measured every month. By deriving the MCCM equations using average rates, we have developed an efficient approach to overcome this problem.

In several synthetic cases with varying skin, long term shut-ins, and frequent mini-shut-ins, the MCCM successfully determined the true connectivity parameters and predicted the production rates accurately. For a set of field data from a heavy oil waterflood in Saskatchewan, we could improve the R^2 of the predicted rates by 20–35% compared to another method and observed good agreement with geological information.

In general, we may not find a long enough time interval of injection and production data where the producers' conditions stay constant. Applying earlier methods in such cases may give misleading connectivity results and inaccurate rate predictions. Adopting the approaches described in this paper helps geoscientists and engineers to have a better understanding of reservoir heterogeneity and its effects on fluid flow in the reservoir.

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1. Introduction

Despite the length of time that waterflood technology has been in use, there are still many surprises when we implement waterfloods: injected water breaks through more quickly than expected, injection supports distant wells while nearby wells are starved, and water escapes to non-productive horizons. These problems often arise because the connectivity between and around wells is poorly understood. Efficient reservoir management, modeling, and exploitation depend on a sound understanding of how the reservoir is 'connected'. The sizes and directions of reservoir flow paths affect drainage effectiveness, well placement, displacement efficiency, and many other factors that influence the economics and environmental impact of resource recovery and fluid placement.

Connectivity can be roughly estimated from observations by field personnel, but changing well conditions (workovers, shut-ins, etc.) confound the analysis. Connectivity is evaluated more accurately using sophisticated geological models and reservoir simulation, but this procedure is costly, time-consuming, and data demanding. To provide fast and cost-effective connectivity evaluations, several investigators have studied the use of injector and

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Nomenclature

Variables

c_t	total compressibility, $(Lt^2)/m$
f	fraction of a time step
I	total number of injection wells
J	well productivity index, $(L^4t)/m$
K	total number of production wells
N	total number of samples (time steps) in the analysis period (window)
p_{wf}	BHP of the producer, $m/(Lt^2)$
q	total fluid rate, reservoir L^3/t
$q(t_0)$	effect of production prior to the analysis period, L^3/t
R^2	coefficient of determination
s	skin segment
t	time, t
V_p	pore volume, L^3
w	injection rate, L^3/t
w'	shifted injection rate, L^3/t

Greek symbols

β	interwell connectivity constant between producer/producer well pair, dimensionless
[B]	matrix of β's, dimensionless
λ	interwell connectivity constant between injector/producer well pair, dimensionless
λ'	corrected interwell connectivity with respect to the homogeneous case, dimensionless
$[\Lambda]$	matrix of λ's, dimensionless
ν	the coefficient of producers' BHP term, L^4t/m
σ	skin effect, dimensionless
τ	time-constant between injector/producer well pair, t
τ_p	time-constant of the effect of production prior to the analysis period, t

Subscripts and superscripts

i	injector index
j	producer index
k	producer–BHP index
m	number of the time step
n	number of the time step of interest
s	segmentation time index
T	matrix transpose
x	shut-in well index

producer flow rates (e.g., Batycky et al., 2008; Fokker et al., 2012) and pressure changes (Tiab and Dinh, 2008) to estimate connectivity. This is an attractive approach because of the abundance of flow rate measurements, even for economically marginal fields, and flow rates contain connectivity information. Most of these investigations have attempted to derive qualitative connectivity measures, such as a correlation coefficient, and plot the results on a map to assess areas of 'high' or 'low' connectivity. Investigators have reported difficulties, however, because their methods show non-physical behavior, such as negative correlations or strong correlations over long distances and short times (e.g., Jansen and Kelkar, 1997; Heffer et al., 1997; Albertoni and Lake, 2003).

Yousef and coworkers developed the capacitance model (CM) to evaluate interwell connectivity in conventional reservoirs (Yousef et al., 2006; Yousef et al., 2009). The CM has the advantage of being able to integrate flow rates and, when they are available, pressure measurements. The CM estimates two parameters, λ and τ, for each injector–producer well pair. These parameters are used to predict production rates (Fig. 1) and estimate interwell connectivities (Fig. 2) for water- or gas-flooded conventional oil fields. In Fig. 2 the arrow length indicates the value of predicted connectivity (λ) and the arrow direction points from the injector to the relevant producer. Numerous reports show that the CM can predict production rates very well (Sayarpour et al., 2009; Weber et al., 2009; Kaviani et al., 2012). The precise values of the λ's and τ's calculated by the CM are relatively unimportant when the CM is only used to predict production rates. The λ's and τ's, however, provide information about the connectivity distribution and can be used with geological data to provide a better understanding of the geological characteristics controlling connectivity. For example in Fig. 2(a) connectivity values for a homogeneous case show symmetry and best connectivity between close wells. But, regions of large permeability (colored areas in Fig. 2b) affect λ's throughout the system.

Since the CM is based on "zero-dimensional" material balance, well geometry is not explicitly included in the model so that the CM estimates production and connectivity for any well configuration. Connectivity estimates may be used to identify well-to-well interactions to adjust, for example, injection rates to improve field economics (e.g., Sayarpour et al., 2009). The well geometry and location, however, have an effect on the interpretation of the interwell connectivities calculated (Fig. 2a). This makes the use of CM connectivities for comparison with geological or seismic maps problematic because the connectivities are a product of both the well configuration and the formation connectivity (Fig. 2b), while the maps reflect only the formation features.

The CM also assumes that the connectivity does not change with time and, in particular, that production well productivity

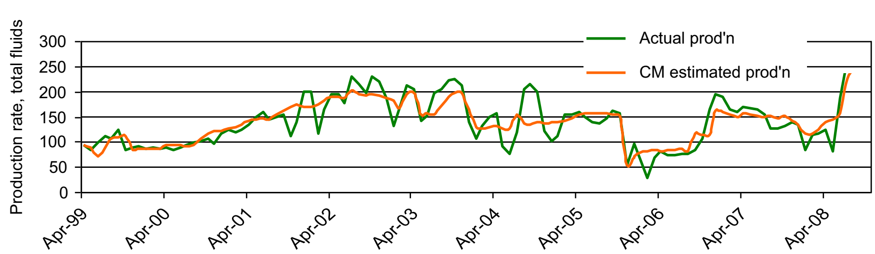

Fig. 1. A typical quality of match between CM-calculated and measured production for one well. The CM estimates are based on injection and production flow rates alone; no reservoir simulation or detailed geological evaluation was needed.

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