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Multilayer capacitance–resistance model with dynamic connectivities

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ABSTRACT

Monitoring vertical and areal distribution of injected water is a key factor to optimize oil production in mature fields. Inter-well connectivities are of fundamental importance to understand such distribution and may help to reveal oversweeped or short-circuited zones. In this paper we develop a new data-driven method to calculate these parameters using production and completion information. We propose a multilayer capacitance–resistance model combined with a simple dynamic model representing the evolution of connectivities with time. This model is automatically calibrated searching for the best fit to historical production rates and incorporates in the description the status of each perforation to drive the evolution of connectivities. This gives a realistic representation of the dynamic nature of inter-well connections and improves the accuracy of existing data-driven models in the literature.

Full numerical simulations of synthetic fields are analyzed with this model showing a good agreement. Moreover, the comparison with previous models in the literature shows that important deviations, encountered when the status of a perforation is changed or when high heterogeneity exists, are corrected by the present technique.

We also exhibit a field example of a mature waterflood consisting of over one thousand wells that shows the advantages of this technique on large datasets where corrections associated to new wells or shut-ins must be included.

Taking into account the low computational effort and data needed for a run, this method could be a wide scope practical tool to estimate inter-well connectivities in mature fields.

1. Introduction

The estimation of inter-well connectivities in mature fields is fundamental to optimize oil production. These parameters give essential information about water distribution in the reservoir and may help to reveal short-circuited well pairs and evaluate sweep efficiency. The estimation of connectivities can be faced in a number of ways. In the full-numerical simulation framework fluid motion in the porous media (Chierici, 1994) is calculated in a discretized reservoir. Although present computers (or clusters of computers) are powerful enough to allow reservoir scale simulations, such methodology requires detailed knowledge of reservoir properties and initial conditions. Thus, the full-numerical simulation framework gives an exact dynamic description of the system but for a set of partially known input parameters that have to be fined tuned to match historical production data (procedure which in fact is an inverse problem that may not be unambiguously solved, Tavassoli et al., 2004). In contrast the aim of simplified data-driven models, such as the capacitance–resistance model (CRM), is to give an approximate representation of the equations that govern the dynamics of the system but using a smaller set of fitting parameters that can be calculated from hard (measured) data. In the particular case of mature fields considered here, we focus on the problem of giving the best possible estimate of inter-well connections using a simple model that can be calibrated with historical injection/production rates and completion data, which are typically the most abundant and reliable registers in the field.

Inter-well connectivity estimates have been studied using production and injection data by Albertoni and Lake (2003). In their incompressible-like model production rates are linear in the unknowns connectivities and the problem of finding a minimum deviation between the prediction and historical data can be easily solved. In this approach some limitations were present, such as negative connectivities generated by their algorithm, or diffusivity filters that have to be applied to simulate compressibility and were not completely integrated in the description. Improvements in the calculation can be achieved with other methods, for example using quadratic programming techniques, but the complexity of the underlying description is still limited by the model. A more complete, but yet simple, model which takes into account compressibility of the porous media and fluids was introduced by Yousef et al. (2006) and Yousef (2005). The CRM can be derived from a discrete material balance in control volumes V_j around producers. It can be shown (Yousef et al., 2006) that the total rate

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$q_j(t)$ of the j-th producer is approximately given by

$$\tau_j \frac{dq_j}{dt} + q_j(t) = \sum_i f_{ij} I_i(t) - \beta_j \frac{dp_j^{(BH)}}{dt} \quad (1)$$

where $\tau_j = c_j V_j / \mathcal{P}_j$, $\beta_j = c_j V_j$, c_j is the total mean compressibility, $\mathcal{P}_j$ is the productivity index of the producing well, f_{ij} is the connectivity between the j-th producer and the i-th injector and $p^{(BH)}$ is the bottom hole pressure (BHP). The best estimates for time constants τ_j and inter-well connectivities f_{ij} associated to a given set of historical data can be calculated minimizing the discrepancy between the model prediction and the data points using a non-linear optimization solver (Weber, 2009; Weber et al., 2009) such as GAMS-CONOPT (GAMS) or other techniques (Liang, 2010). In this way the parameters in the model can be calculated from the history match procedure in an overdetermined way if the injection data varies enough (see Yousef, 2005 and Appendix). The resulting methodology has been successfully applied to study and optimize production in many cases (i.e. Sayarpour et al., 2009; Nguyen et al., 2011) where the underlying assumptions remained approximately valid.

In this paper we develop a model that contains the mono-layer CRM with constant inter-well connections as a particular case and thus goes beyond the range of situations that can be explored with it. Specifically, all the parameters in the CRM are fixed and do not distinguish layer differences in the reservoir. Thus, under those assumptions, water redistribution after a productive layer is open or shut is not taken into account, and consequently inter-well connectivity changes due to modifications in the pressure gradient field are averaged out. Here we incorporate reservoir layering into the model and upgrade inter-well connections to a dynamic variable as well. In particular, we combine a multilayer CRM with a simple model to drive the evolution of connectivities with time, thus being able to consider all changes in well completions to build a consistent dynamical picture. The comparison of this scheme with full numerical simulations of synthetic fields shows that important deviations of the mono-layer CRM with constant parameters, are corrected using the present technique. A field example is also presented here where the same observations apply.

2. The model

In this section we derive the flow equations used to describe the system and sketch how we solved the fitting problem. The performance of particular implementations of the model discussed here will be compared in the next section with full numerical simulations of synthetic waterfloods.

2.1. Dynamical equations

Let us consider a reservoir that can be subdivided into L hydraulically uncoupled layers, generically denoted by α. We will study the problem of M injectors and N producers that can exchange liquid, in principle, via any of those layers. To describe the status of a perforation (completion data) we introduce a function $\mathcal{S}_{j\alpha}(t)$ such that $\mathcal{S}_{j\alpha}(t) = 1$ for an open layer in the $\alpha-$th level of the j-th producer, and $\mathcal{S}_{j\alpha}(t) = 0$ in the complementary case. The dynamics of inter-well connections $f_{ij\alpha}(t)$ will depend on this set of data. A material balance in a control volume $V_{j\alpha}$ for each layer α of the producer j, is shown in Fig. 1. Liquid contribution of the i-th injector to that volume reads

$$f_{ij\alpha}(t) I_{i\alpha}(t), \quad (2)$$

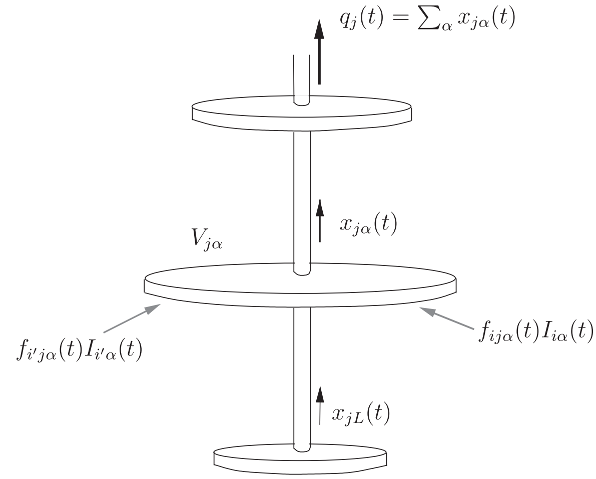

Fig. 1. Multilayer capacitance–resistance model. The total rate $q_j(t)$ results a sum of contributions $x_{j\alpha}(t)$ from active layers which are approximately described by a CRM. The producer is connected to the injectors through dynamic connectivities $f_{ij\alpha}(t)$.

while the rate of liquid produced is given by $x_{j\alpha}(t)$ when the layer is open[1] ($\mathcal{S}_{j\alpha}(t) = 1$). Thus, the mean reservoir pressure $p_{j\alpha}$ associated to the volume will change according to

$$c_{j\alpha} V_{j\alpha} \frac{dp_{j\alpha}}{dt} = \sum_i f_{ij\alpha}(t) I_{i\alpha}(t) - x_{j\alpha}, \quad (3)$$

where $c_{j\alpha}$ is the total mean compressibility. The mean reservoir pressure is not accessible, so we have to include another equation coupling the reservoir to the boundaries. When the layer is closed ($\mathcal{S}_{j\alpha}(t) = 0$) the boundary condition is trivial:

$$x_{j\alpha} = 0. \quad (4)$$

In contrast, when $\mathcal{S}_{j\alpha}(t) = 1$, a non-trivial condition have to be imposed. The simplest possible model that links the total rate produced by the volume $V_{j\alpha}$ with the BHP reads

$$x_{j\alpha} = \mathcal{P}_{j\alpha}(p_{j\alpha} - p_{j\alpha}^{(BH)}), \quad (5)$$

where $\mathcal{P}_{j\alpha}$ is the productivity index. Thus when $\mathcal{S}_{j\alpha}(t) = 1$ we can decouple Eqs. (3) and (5) (as it is done in Yousef et al., 2006 for a single layer) finding a first order ordinary differential equation with constant coefficients that approximately describes the evolution of the rates $x_{j\alpha}(t)$:

$$\tau_{j\alpha} \frac{dx_{j\alpha}}{dt} + x_{j\alpha} = \sum_i f_{ij\alpha}(t) I_{i\alpha}(t) - \beta_{j\alpha} \frac{dp_{j\alpha}^{(BH)}}{dt}, \quad (6)$$

where $\tau_{j\alpha} = c_{j\alpha} V_{j\alpha} / \mathcal{P}_{j\alpha}$ and $\beta_{j\alpha} = c_{j\alpha} V_{j\alpha}$. Thus, the dynamical equations for the rates $x_{j\alpha}$ are given by

$$x_{j\alpha} = 0 \quad \text{if } \mathcal{S}_{j\alpha}(t) = 0 \quad (7)$$

and

$$\tau_{j\alpha} \frac{dx_{j\alpha}}{dt} + x_{j\alpha} = \sum_i f_{ij\alpha}(t) I_{i\alpha}(t) - \beta_{j\alpha} \frac{dp_{j\alpha}^{(BH)}}{dt} \quad \text{if } \mathcal{S}_{j\alpha}(t) = 1. \quad (8)$$

Note that whenever a layer is open at $t = \hat{t}$, a new initial rate $x_{j\alpha}(\hat{t})$ has to be introduced. Contributions $x_{j\alpha}$ of Eq. (8) can be either positive or negative. In the latter case they account for cross-flow between layers when an over-depleted layer exists (although, for typical mature waterfloods, the fill up period is completed and contributions result positive).

[1] Note that all rates should be calculated at reservoir conditions.