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RESEARCH PAPER

Application of capacitance resistance models to determining interwell connectivity of large-scale mature oil fields

JAMALI Ali, ETTEHADTAVAKKOL Amin*

Texas Tech University, Lubbock, TX 79409, USA

Abstract: In view of the problems existing in the application of Capacitance Resistance Models (CRMs) to large-scale mature oil fields, Capacitance Resistance Model for Producers (CRMP) was selected for analysis, a simplified procedure for applying CRMP to large-scale mature oil fields was proposed, and some examples were analyzed. Several strategies were presented to optimize the solution method, in order to shorten the solution time and speed up convergence rate. These include the implementation of a global optimization algorithm, parameter scaling, and analytical development of gradient vector and Hessian matrix of the CRMP objective function. These improvements enable the application of CRMP to large-scale problems. Stepwise history matching was shown to be an effective technique to improve reliability of the analysis. Our analysis shows that, the connectivity obtained by the presented method agrees with the interpreted connectivities from the observed CO_2 injection and production signals, which proves the reliability of the presented method. The connectivity of an injector to the nearby producers can be analyzed based on the CRMP results, and the analysis can be used for related studies, such as determining current water injectors suited for CO_2 injection, or current CO_2 injectors not suited for CO_2 injection.

Key words: capacitance resistance model; mature oil field; interwell connectivity; enhanced oil recovery

Introduction

Analyzing injector-producer pairs to determine reservoir characteristics has a long history, and includes several methods, including tracer testing and/or monitoring producers' response to an injection signal. Some researchers used statistical methods along with injection and production data to determine interwell communication[1–3]. Heffer et al.[1] calculated the Spearman rank correlation coefficient between injector-producer pairs to find the interaction between them as a potential measure of flow directionalities. Their analysis indicated that the injection signal received by producers have some components coupled to geomechanics. Panda and Chopra[2] used artificial neural networks to predict oil production rate and to estimate the interaction between well-pairs. They applied this method to small simulation case studies and concluded that the application of artificial neural networks to such complex systems has some limitations. In addition, it is well known that the physical interpretation of such models is a challenge. Albertoni and Lake[3] used the multivariate linear regression analysis to quantify the interwell communications.

Yousef et al.[4] developed a mathematical model to calculate producers' total fluid production responses to injection signals and bottomhole pressure variations. This model was essentially the solution to the mass balance differential equation for a closed control volume containing a set of injectors and producers. The model contains some unknown coefficients that relate the production response to the producers' effective drainage volume, fluid compressibility, productivity index, and the connectivity coefficient between the injector-producer pairs. These parameters can effectively describe the capacity of the system to produce fluid. Because there is a unique similarity between this model and the equation used to describe the flow of electrical currents in a system of capacitors and resistors, this model and its variations known as Capacitance Resistance Model (CRM). Sayarpour et al. [5] expanded the solution of the mass balance differential equation to three different control volumes, namely the entire field (CRMT), a single producer (CRMP), and an injector-producer pair's shared volume (CRMIP), and coupled CRM with fractional flow model to predict the oil production rate of each producer and the total fluid production rate.

The application of CRMs to large-scale problems faces several challenges affecting the accuracy and reliability of the results. The early studies limited the problem size to a subset of less than 60 wells to keep the optimization problem in manageable size. Weber et al.[6] proposed several heuristic solutions to reduce the problem size, including the removal of inactive wells and restraining the connectivity by setting a

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*** Corresponding author.** E-mail: amin.ettehadtavakkol@ttu.edu

connectivity radial cutoff, and in light of a reduced problem size, they suggested that the result of nonlinear regression is more likely to be statistically significant. Nguyen et al.[7] introduced the Integrated Capacitance Resistance Model (ICR) with a linearized objective function, and concluded that the ICR would converge to a unique solution regardless of the number of fitting parameters because it uses linear regression.

In this study, solutions for some of the issues encountered in the application of the technique in large scale mature oilfields have been put forward, a simplified procedure for applying CRMs to mature oil fields has been proposed, and the methodology has been applied to several leases located in Slaughter field, West Texas, and the results are presented.

1. Features of mature oil fields

The problem investigated in this paper is commonly encountered in mature oil fields which have undergone waterflood or CO_2-EOR for a long period of time and possess the following characteristics:

• The current drilling activity is very low, but the injector/producer interruptions are frequent due to high workover and maintenance activities.

• A variety of artificial lift techniques can be used; however, the majority of producers are producing with sucker rod pump. The application of such pump guarantees that the fluid level and consequently the flowing bottomhole pressure varies within a relatively small range.

• The oilfields have a fairly dense well spacing of 10-30 acres and there are no further plans for drilling new wells.

Approaching a marginal oil recovery, these fields usually suffer from declined oil production, excessive water/CO_2 production, and many other problems. CRMs can be used to evaluate these fields at low cost and high speed, to minimize investment risks for operators in the late stage of oilfield development.

2. Simplified procedure

The CRM formulation has been presented in detail in the literature [4–5]. Consulting the previous method, a simplified derivation method is presented in this paper based on single phase assumption of slightly compressible fluid. The isothermal compressibility factor of fluid is defined as the relative volume change of fluid with pressure at constant temperature. For any reservoir system with injectors and producers (Fig. 1a), assuming the reservoir fluid is single phase, the total compressibility factor c_t is used to describe the fluid:

$$c_{\mathrm{t}}=-\frac{1}{v_{\mathrm{p}}}\frac{\mathrm{d}v_{\mathrm{p}}}{\mathrm{d}\overline{p}}=-\frac{1}{v_{\mathrm{p}}}\frac{\mathrm{d}v_{\mathrm{p}}}{\mathrm{d}t}\frac{\mathrm{d}t}{\mathrm{d}\overline{p}} \tag{1}$$

For a closed system with only one producer and one injector, the accumulation of the fluid in the system is the sum of injected volume and produced volume:

$$-\frac{\mathrm{d}v_{\mathrm{p}}}{\mathrm{d}t}=I-Q=c_{\mathrm{t}}v_{\mathrm{p}}\frac{\mathrm{d}\overline{p}}{\mathrm{d}t} \tag{2}$$

Well test analysis is required to determine the average formation pressure, therefore, continuous data can't be obtained. It is often assumed that waterflooding reservoirs have steady flow features, however, because of frequent shut-down of injector and producer, this is assumption is not accurate. Therefore, linear productivity model is adopted to remove average pressure item to reduce the complexity:

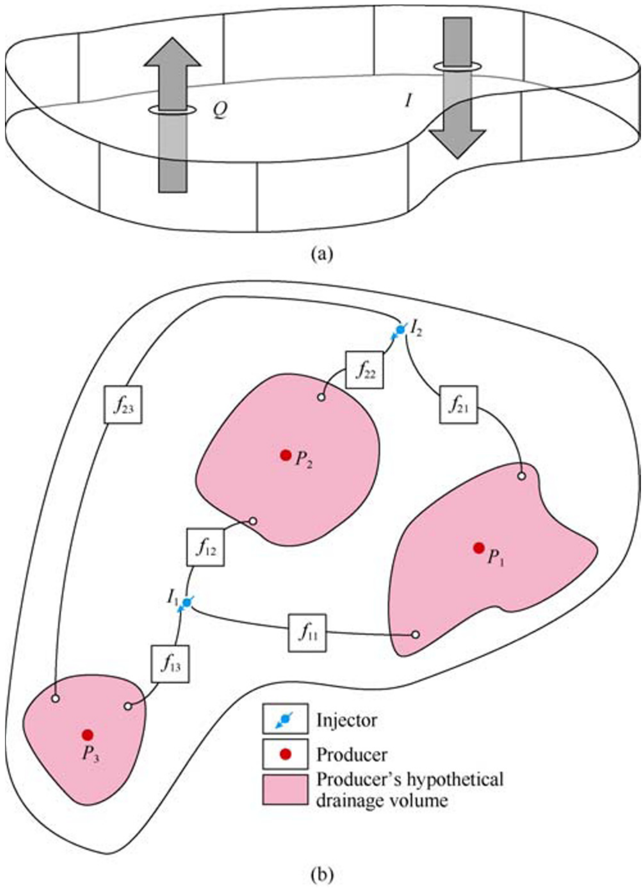

Fig. 1. Schematic of the base CRM (a) and schematic of CRMP (b).

$$\overline{p}=\frac{Q}{J}+p_{\mathrm{wf}} \tag{3}$$

Substituting Eq. (3) into Eq. (2), we get:

$$\frac{c_{\mathrm{t}}v_{\mathrm{p}}}{J}\frac{\mathrm{d}Q}{\mathrm{d}t}+c_{\mathrm{t}}v_{\mathrm{p}}\frac{\mathrm{d}p_{\mathrm{wf}}}{\mathrm{d}t}=I-Q \tag{4}$$

Define time constant τ as:

$$\tau=\frac{c_{\mathrm{t}}v_{\mathrm{p}}}{J} \tag{5}$$

Make $\mathrm{e}^{t/\tau}=\mathrm{e}^{\int(1/\tau)\mathrm{d}t}$ the integrating factor, we get the solution of Eq. (4):

$$Q(t)=Q(t_1)\mathrm{e}^{-\frac{t-t_1}{\tau}}+\frac{\mathrm{e}^{-\frac{t}{\tau}}}{\tau}\int_{t_1}^{t}\mathrm{e}^{\frac{\xi}{\tau}}I(\xi)\mathrm{d}\xi+J\left[p_{\mathrm{wf}}(t_1)\mathrm{e}^{-\frac{t-t_1}{\tau}}-p_{\mathrm{wf}}(t)+\frac{\mathrm{e}^{-\frac{t}{\tau}}}{\tau}\int_{t_1}^{t}\mathrm{e}^{\frac{\xi}{\tau}}p_{\mathrm{wf}}(\xi)\mathrm{d}\xi\right] \tag{6}$$

2.1. Discrete producer model

To determine injector-producer interaction, the model is extended for individual producers. It is assumed that a certain