Computers & Geosciences 55 (2013) 96–109

Contents lists available at SciVerse ScienceDirect

Computers & Geosciences

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

Information content in Lagrangian sensor measurements for reservoir characterization

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ARTICLE INFO

Article history:
Received 9 January 2012
Received in revised form
1 May 2012
Accepted 12 May 2012
Available online 24 May 2012

Keywords:
Model resolution
Nanosensor
Ensemble Kalman filter
Lagrangian sensor
Information content
Iterative EnKF

ABSTRACT

The prospect of injecting particles or sensors of sufficiently small size into reservoirs for improved reservoir characterization has become an active topic of research, yet little is known about the possible improvements in model resolution or reduction in uncertainty that could be achieved through in-situ sensor observations. In this paper, we investigate the information content provided by potential repeated measurements of particle pressure and/or location for particles that are transported passively with an injected fluid in heterogeneous reservoirs.

Observations of locations of drifting particles at relatively frequent intervals provide substantial reduction in uncertainty in reservoir properties, except in regions through which the particles are unable to travel. Low permeability regions within flow zones, however, do affect the flow paths and are mapped relatively well through assimilation of the data. Pressure observations appear to be much less useful than observations of location, except in the neighborhood of wells where pressure gradients are quite high. The reservoir properties near the well, however, can be estimated relatively well using pressure data at wells.

The results of this study show quantitatively that potential Lagrangian sensor measurements can provide additional information compared to standard production data for reservoir characterization. Despite the small size of the sensors, the model resolution is limited due to the spatial averaging in the sensitivity of the Lagrangian data to reservoir model parameters. High frequency of sensor measurements can improve the model resolution, but the improvement is marginal unless the accuracy of the measurements is quite high.

1. Introduction

Good reservoir characterization of rock property distributions is key to improvement in oil recovery and reservoir management, especially for secondary and tertiary recovery processes in which oil may be displaced by another fluid. Knowledge of the regions of the reservoir with substantial remaining oil is also important, as these areas could be targeted for infill drilling or improved recovery through realignment of flow directions. The reservoir can only be directly observed at locations where wells are drilled, and the resolution of estimates of rock properties between wells from measurements at wells is generally poor. As a consequence, there is a large effort within the oil industry to develop new types of measurements that can probe deeper into the reservoir. In particular, we note the effort to develop sensors that can be injected into the reservoir to provide in situ measurements in regions that are not otherwise assessable (Ullo, 2008; Chapman and Thomas, 2010). While sensors with a broad range of functionalities are being investigated, we focus on the potential information content from sensors that drift with the injected fluid and whose location can be determined and which can measure the pressure of the surrounding fluid. The precision of the measurements from these sensors will probably not be very high because of the size limitations, but the potential ability to place them in the interior of the reservoir makes the information potentially valuable for detailed reservoir characterization.

The objective of the paper is to analyze the additional information about the reservoir properties that would be provided by nanosensors compared to conventional well data. We emphasize that these sensors have not yet been fully developed, so that the value of an investigation of the information content of potential sensors is to guide research efforts and the sensor design process. In order to determine how useful the information from these potential sensors might be, we model transport and observations from heterogeneous reservoirs under a set of fairly idealized assumptions. In particular, our modeling is done at the

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http://dx.doi.org/10.1016/j.cageo.2012.05.013

macro-scale and we have neglected effects of finite particle size and interfacial effects. For simplicity, we assume that only a single fluid phase is present and that the nanosensors travel with the injected fluid in the reservoir. The analysis of information content is based on a synthetic example in which the same model used to generate data is used for estimation, so there is no model error. In addition, we make some fairly optimistic assumptions on the potential functionality of the nanosensors. For this investigation, we have assumed that it will be possible to track the movement of an individual particle over time with an accuracy of approximately ± 7 m. Note that this is a somewhat stronger assumption than assuming that concentration of a contrast agent can be observed accurately. We have also assumed that the pressure can be measured at seven different times on each particle. For the types of sensors that are envisioned to be feasible (Metzger et al., 2010), it is likely that only a single measurement will be possible but then we must assume that some of the nanosensors are set to record pressures at different times, perhaps through the use of chemical coatings. Many of the assumptions are quite optimistic, so our evaluations can be expected to be the "best case". If nanosensors cannot provide the necessary information with these hypothesized functionalities and under the idealized modeling assumptions, then it can be assumed that the results will be worse in more realistic situations.

The data assimilation problem we envision differs from most history matching problems in which the locations of observations are known. The problem we address is one in which the sensors are drifters whose locations at various times provide useful information. Data assimilation problems with Lagrangian sensors (drifters) have been previously addressed in oceanography (Molcard et al., 2003; Salman et al., 2006; Apte et al., 2008) and shallow water flow (Rafiee et al., 2011). The potential for bifurcation of drifter trajectories makes the assimilation problem potentially highly nonlinear, in which case hybrid data assimilation methods may sometimes be required (Salman et al., 2008). In reservoir flow, eddies are non-existent and experience so far has been that the sequential assimilation of location observations for drifting nanosensors is sufficient to keep the inverse problem in the regime where linear updates to model variables are appropriate. In the current investigation, we use the ensemble Kalman filter (EnKF) to assimilate the sensor data. The EnKF was originally applied to data assimilation in oceanography and numerical weather prediction (Evensen, 1994, 2009), but has been used for petroleum reservoir model history matching and uncertainty quantification since 2005 (Nævdal et al., 2005). Comprehensive reviews of the application of the EnKF in petroleum reservoir history matching can be found in Aanonsen et al. (2009) and Oliver and Chen (2011).

In a previous paper (Stordal and Oliver, 2011), we examined information content for particles in flow that was constrained to a one-dimensional path with fixed injection rate. In that case, the pressure observed by the particles was highly informative as it provided information on both permeability and porosity (indirectly through location estimation). Because of the boundary conditions and the restriction to one dimension, measurements of the location of the particle only provided information on the porosity between the injection point and the observation point. The location information provided no information on the permeability. In that paper, we quantified the information content through estimates of the spatial resolution of the parameter estimates. In the current paper, the value of various types of sensor measurements will be based on the reduction in the variance of the estimates and on model resolution, which provides the link between the estimated properties and the true reservoir properties (see Oliver, 1996, for an example related to transient pressure information). The spread of the model resolution provides an estimate of the degree of averaging of the truth contained in the estimate.

This paper is organized as follows. In Section 2, we describe a fairly generic forward model that is used for investigation of information content. While the conclusions about the importance of various aspects of the sensors will depend on the values of the parameters describing the model, the parameters have been chosen to be in the realistic range. In Section 3, we investigate the sensitivity of particle location and particle pressure to permeability and porosity in a heterogeneous reservoir. This provides insight into the usefulness, as a lack of sensitivity implies a lack of information. Then in Section 4 we describe the results of joint assimilation of sensor location and pressure, assimilation of sensor pressure alone, and for comparison, the results for assimilation of well pressures alone. Model resolution for the different sensors are compared in Section 5.

2. Forward modeling

We consider single phase flow satisfying the continuity equation and Darcy's law

$$S_s \frac{\partial h(\mathbf{x},t)}{\partial t} + \nabla \cdot (K(\mathbf{x}) \nabla h(\mathbf{x},t)) = q(\mathbf{x},t) \tag{1}$$

subject to the initial and boundary conditions. In Eq. (1), $q(\mathbf{x},t)$ is the sink/source and $h(\mathbf{x},t)$ is hydraulic pressure head. The specific storage, $S_s(\mathbf{x})$, and the hydraulic conductivity, $K(\mathbf{x})$, are both heterogeneous spatially correlated rock property fields. The flow equation is solved using the finite difference method by MODFLOW (Harbaugh et al., 2000). We make the assumption that nano-particles travel with the fluid in the reservoir. A particle-tracking postprocessing package MODPATH (Pollock, 1994) is used to compute particle locations with time given the initial position of the particles. The particle pressure is the reservoir pressure at the location of the particle. MODFLOW computes pressure head at the center of each cell, and fluxes crossing the cell faces. MODPATH uses velocity at the cell faces to linearly interpolate the x, y, z velocity component at internal points of a cell. For steady state flow, the exiting location and exiting time of a particle from a cell can be easily calculated and the computation continues in the subsequent cells. Transient flow is treated as a composite of a sequence of steady state flow with velocity computed at each time step. In this study, we consider steady state flow.

In single-phase steady state flow, the pressure and flux fields are determined by the hydraulic conductivity (K), so the path of a particle given its starting position is determined by hydraulic conductivity. The velocity of a particle along its path is, however, determined by both hydraulic conductivity and porosity ϕ. The numerical model used throughout the paper is two-dimensional with 41×41 gridblocks. The size of each gridblock is 20×20 m^2. The thickness of the model is 1 m. There is an injector at the center of the domain and four producers near the corners. The particles are injected with the injection fluid and move with the injection fluid towards the producers. At sinks and sources, i.e. model gridblocks that contain producing and injection well, linear interpolation over large distances is not adequate to accurately describe the velocity distribution of the gridblock. Since velocity near the injector determines the initial moving directions of the particles, the center gridblock of the coarse grid is refined to 5×5 gridblocks, so that the cell containing the injector has dimensions 2×2 m^2, the eight gridblocks on the next circle have dimensions 4×4 m^2 and the next circle of gridblocks has dimensions 5×5 m^2. To model the injection of particles with the injection