Parameter estimation and uncertainty quantification for core flooding

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Problem background

In petroleum reservoir engineering waterflooding is a technique to enhance the oil recovery from a reservoir. In waterflooding water is injected in one or more places (injection wells) in a reservoir under high enough pressure for the oil in the reservoir to be pushed by the injected water towards the producing wells of the reservoir. If one knows the relevant data such as rock and fluid properties, it is possible to predict the resulting water and oil production using a simulation model.

Consider for instance waterflooding in one space dimension. At one end water is injected and at the other end oil and water are produced. We assume oil and water to be incompressible. The two-phase flow model of incompressible fluid flow through a porous medium in one space dimension is here given by the transport equations for the phase masses for oil and water (w=water, o=oil),

$$\frac{\partial}{\partial t}\left(\phi \rho_o S_o\right) + \frac{\partial}{\partial x}\left(\phi \rho_o v_o\right) = 0,$$

$$\frac{\partial}{\partial t}\left(\phi \rho_w S_w\right) + \frac{\partial}{\partial x}\left(\phi \rho_w v_w\right) = 0,$$

and Darcy's equations,

$$q_o = -\frac{k k_{ro}}{\mu_o}\frac{dp_o}{dx} = -\lambda_o \frac{dp_o}{dx},$$

$$q_w = -\frac{k k_{rw}}{\mu_w}\frac{dp_w}{dx} = -\lambda_w \frac{dp_w}{dx}.$$

These equations are written in terms of the fluid phase pressures (p_o and p_w) and the fluid phase volume fractions (the saturations S_o and S_w), which need to be solved from these equations given appropriate data. The actual velocities v_i are related to the Darcy (or superficial) velocities q_i by $q_i = \phi v_i$. Additionally, we require that the saturations add to one:

$$S_o + S_w = 1.$$

Due to surface tension the oil and water pressures are not equal. The difference between the two pressures is the capillary pressure, p_c:

$$p_c = p_o - p_w.$$

Furthermore, the reservoir is taken horizontal: the effect of gravity is neglected. The densities ρ_o and ρ_w are constant, as are the porosity ϕ, the absolute permeability k and the viscosities μ_o and μ_w.

The relative permeabilities (or "relperms") k_{ro} and k_{rw} and the capillary pressure p_c are modelled as functions of the water saturation. These functions vary from (oil) field to field and so are not known exactly in advance. In practice, these functions of the saturations are determined in an experimental setup: a piece of rock ("core") is taken from the reservoir at hand and in a laboratory the oil is pushed out from the core by injected water in a controlled experiment. This core flood experiment is done such that a one-dimensional description can be used to model the two-phase flow through the rock. In the one-dimensional model some functional model is assumed for the relative permeabilities and the capillary pressure and the experiment is simulated with those coefficients. By comparing the outcome of the one-dimensional model with the experiment it is possible to improve the model for the coefficients until a best fit is achieved. The estimated parameters are then used in the reservoir simulation model for that reservoir.

Assignment

This assignment is about the uncertainty quantification (UQ) in core flood simulations. Input parameters are uncertain and it is important to see how the uncertainty is reflected in the model output. On the other hand, parameter estimation for relperm and capillary pressure models are based on the core flood model and the experiments, which also have an uncertainty, and so it is also interesting to assess the parameters' sensitivities and uncertainties. It is also desirable to understand the inter-parametric dependency, since relperms and capillary pressures are not independent. Furthermore, the parameter estimation problem is an ill-posed optimization problem and insight into the nature of the ill-posedness may be worth investigating. Also the presence of local minima and the role of the initial guess as well as the choice of parametrization of the relperms and the capillary pressure curves are expected to have a significant effect on the quality of the parameter estimation. For instance, it is important that monotonicity of the curves is guaranteed whenever the data are monotone, despite the uncertainty in the data. Many questions can be asked. For instance, which measurements are the most important ones for the parameter estimation. How should the measurements be set up for good estimation without doing too much? What is the influence of the numerical method or the model used?

The data for the parameter estimation can come from various experiments, and hence may have quite different uncertainties. This should be taken care of. Furthermore, there may be data outliers. What to do with outliers: is there a systematic way to handle them? One way of handling them may be through the objective function.

The idea is to develop a tool that can handle the UQ of a core flood model, as well as the parameter estimation routine. The numerical method used to do the parameter estimation could be based on an Ensemble Kalman Filter (EnKF) method. The parameter estimation problem is formulated as a constrained optimization problem where the objective function reflects the mismatch between the measurements and the model outcome, and hence has to be minimized.

A desirable feature of the tool is the presentation and visualization of the uncertainties in the data and model results.

If possible the UQ study should be applied to a real-life data set.

Literature

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