SIMULTANEOUS DETERMINATION OF ABSOLUTE AND RELATIVE PERMEABILITIES

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Introduction. Data from core analyses, such as residual oil saturation and relative permeability, are of great importance for proper exploitation of the petroleum resources. Such quantities are typically determined through interpretation of data acquired during some flooding experiment. In such determinations, the absolute permeabilities are typically represented by a single average value, i.e., the core is assumed homogeneous and isotropic. Recent studies[4], however, show that the validity of such assumptions can be questioned, and the obtained results will depend on the actual core sample heterogeneity, i.e., the variation and distribution of the absolute permeability in the core. A better option will then be to determine the absolute and relative permeabilities simultaneously from the data. Hence, in the estimation procedure for relative permeability one would account for a possible spatial distribution of the absolute permeability. In this paper we describe and test a method for such determinations, and discuss some results. Simultaneous estimation of absolute and relative permeabilities have been tested using simulated[1] two-phase flow data. The data utilized are time series of pressure drop, volume produced, and pressure measurements on four points along the core. The estimation procedure utilized is a regression-based approach, in which the experimental data are reconciled by simulation[2,5]. This method performs a sequential history matching procedure, determining successively better estimates of the relative permeabilities (functions of saturation) and absolute permeability (spatially varying) from the measured data. Our results show that better data reconciliation by simulation results when a spatially varying absolute permeability is allowed for in the estimation procedure.

Simultaneous Estimation. We focus our initial investigation of simultaneous estimation of absolute and relative permeability around the composite core case. This is interesting from a core analysis point of view, as composite cores typically are utilized in the industry. Resent findings[4], indicate that large errors will result if the permeability in the individual sample in the composite deviate from the mean permeability value. In some cases a relatively small deviation will suffice[4].

By simultaneous estimation of absolute and relative permeabilities, we account for a potential variation of the absolute permeability in the core sample. The data used to perform such estimations must contain information about the heterogeneity as well as the fluid flow of several phases. This is achieved by utilizing data from a steady-state, two phase flow experiment on the composite core illustrated in Fig. 1[3]. The core has an initial water saturation of 10%. The saturation range represented in the data increases with increasing oil/water fraction. In the first rate step, water and oil are injected simultaneously into the core with a low water fraction. After some time the water fraction is increased, and finally, the water fraction is set to unity. Fig. 2 shows the actual data utilized in this analysis.

[1]Simulated cases have been considered. The data were generated utilizing a 1D simulator with a set of true relative permeability curves and true permeability variation implemented. Random errors with zero mean and a given standard deviation were added to mimic the measurement process. The standard deviations were chosen according to the size of typical measurement errors[4].

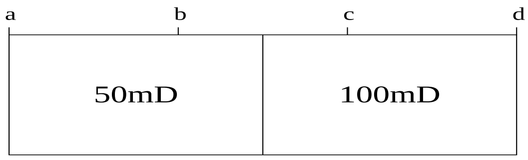

Figure 1: *The 1D permeability distribution of the composite core studied.*

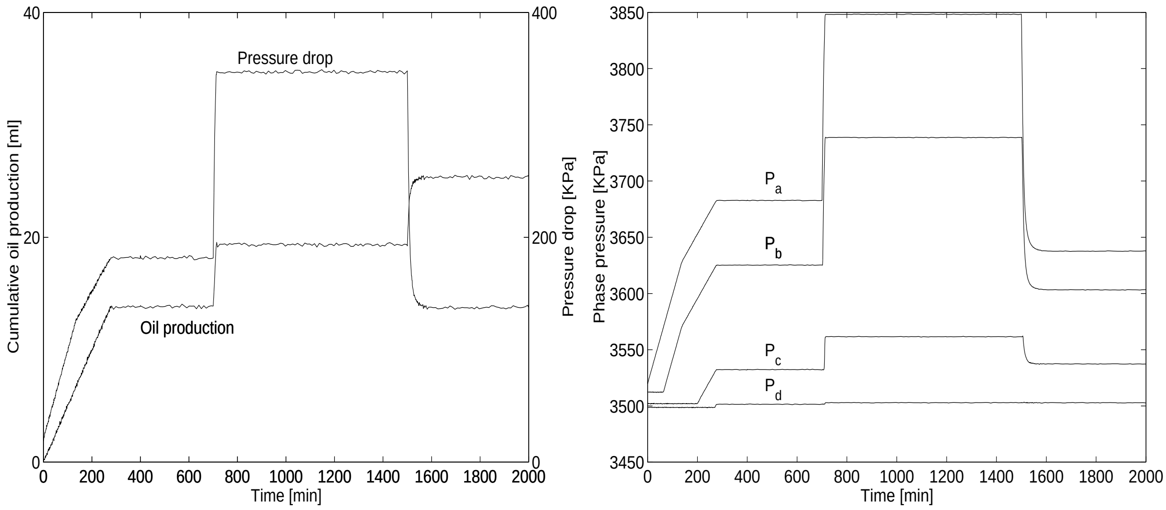

Figure 2: *Pressure drop and production data (left). Phase pressure measurements along the core (right).*

Left are the production and pressure drop data, and right are the pressure measurements along the core.

Considerable studies on estimation of the relative permeabilities have been conducted over the past more than ten years[3,4,5]. We use the same technique to estimate the relative permeabilities in this work: The relative permeabilities are represented by B-splines. The parameters (coefficients) in this representation are estimated from the data through solution of a series of non-linear least-squares problems, the idea being that the simulated data should reconcile those actually measured. The absolute permeability is represented by the Haar basis, which is a multi-scale representation[1]. With this representation the various terms in the property function series represent variation on different length scales. The first term (scale 0), a single parameter, represents the average permeability over the entire reservoir, and is estimated first. Next (scale 1), the averages in the two halves (1D) of the structure is estimated, with the previous scale-estimate as initial value, and so on. The permeability is hence estimated on successively finer scales from the dynamic data in a sequence of history matching problems with increasing spatial resolution. We have combined the estimations of absolute and relative permeabilities described above. Fig. 3 illustrate the schematics of the estimation procedure[2]. The absolute and the relative permeabilities are estimated successively. First the relative permeabilities are estimated utilizing the harmonic mean value of the absolute permeability. Then the absolute permeability is estimated, keeping the relative permeabilities fixed at their first estimates. We then return to the relative permeabilities, keeping the absolute permeability fixed at its latest estimate. This procedure is repeated several times. Thus, successively more accurate estimates for the absolute and the relative permeabilities are determined. This continues until the information content in the data is fully utilized, we then have determined the final estimates. Note that both the absolute and the relative permeabilities are determined from the measured data by this implicit, regression-based method.

To validate an estimate we utilize statistical measures such as the sum of squared residuals, the number of runs, and 95% confidence intervals[4]. To accept an estimate the sum of squared residuals and the number of runs should approach some calculated limits[2]. The estimate should also be close to the true curves, and have narrow confidence intervals[4].

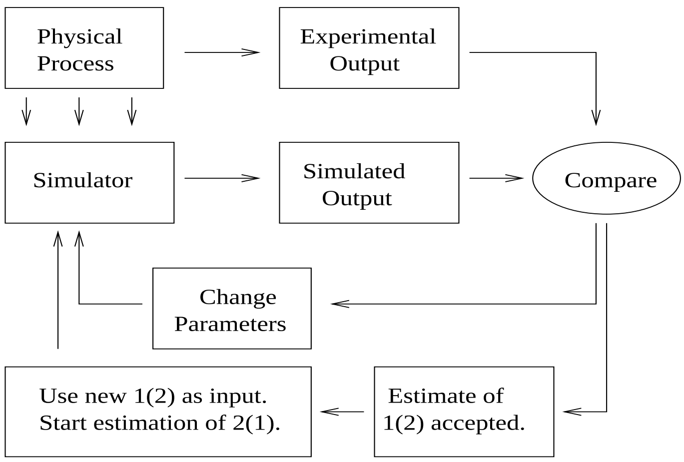

Figure 3: *Schematics of the Simultaneous estimation.*

Results and Discussion. The estimation procedure described above is tested on the simulated experimental data in Fig. 2. We have kept the capillary pressure constant and equal for both the individual cores in the composite. In practice the capillary pressure will vary in a heterogeneous core. We have here idealized the situation, to concentrate our initial studies on the effect of the permeability alone. Fig. 4 shows three sets of relative permeability curves as a function of saturation: The true ones (those utilized to generate simulated data), the ones estimated by utilizing the harmonic mean, and the final estimates achieved by the successive approach described above. Utilizing the harmonic mean results in relative permeability curves deviating from the true ones. These are not acceptable estimates according to their calculated statistical measures. When estimating the relative permeabilities the harmonic mean does not provide sufficient information about the permeability variation. The the final

[2]In the figure the relative and absolute permeability are referred to as (1) and (2), respectively.

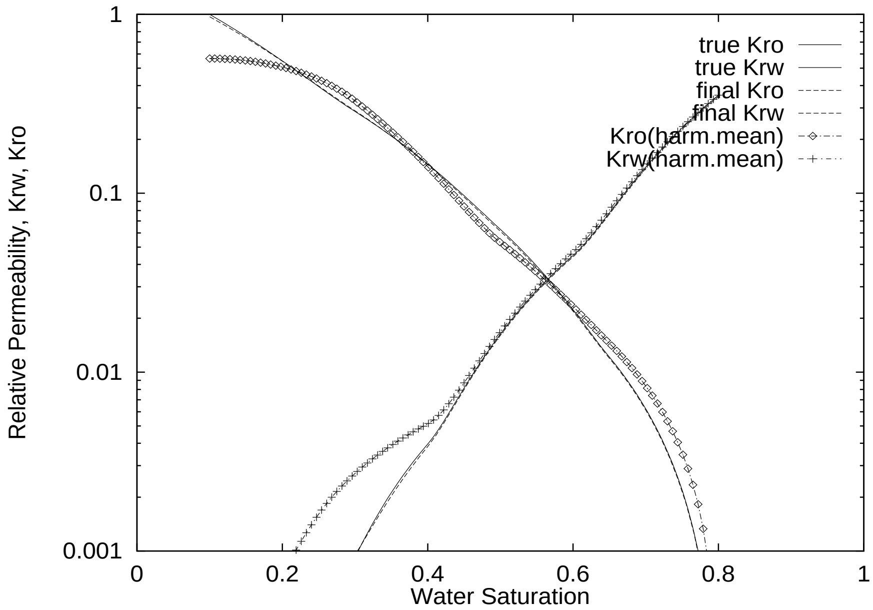

Figure 4: *Estimated and true relative permeabilities.*

estimate from the successive approach are, however, acceptable. They are close to the true curves, and their calculated sum of squared residuals and number of runs are acceptable. They also have narrow 95% confidence intervals.

The final relative permeability estimates were established utilizing the final absolute permeability estimate from the successive approach. This is shown in Fig. 5. Nine successive estimations are performed to establish the final absolute and relative permeabilities. To illustrate how the estimation progresses, we study the estimation of permeability distributions determined by utilizing four different sets of estimated relative permeability curves. Each set of different relative permeability curves provides estimated permeability distributions on several scales. Fig. 6 show the sum of squared residuals as a function of scale for these estimates. The results utilizing the true relative permeabilities are also shown. To accept an estimate, the sum of squared residuals should approach the limit represented by the solid horizontal line in the figure. Utilizing the true relative permeabilities provides calculated values for the scale 3 and scale 4 distributions approaching this limit. The calculated values for scale 1, scale 2, scale 3 and scale 4 of the fourth estimates also approaches the limit. The calculated value on scale 1 of the fourth estimates, correspond to the final estimate in Fig. 5. The calculated sum of squared residuals and number of runs for the final estimate are acceptable. This estimate is also close to the true permeability, and has a narrow 95% confidence interval.

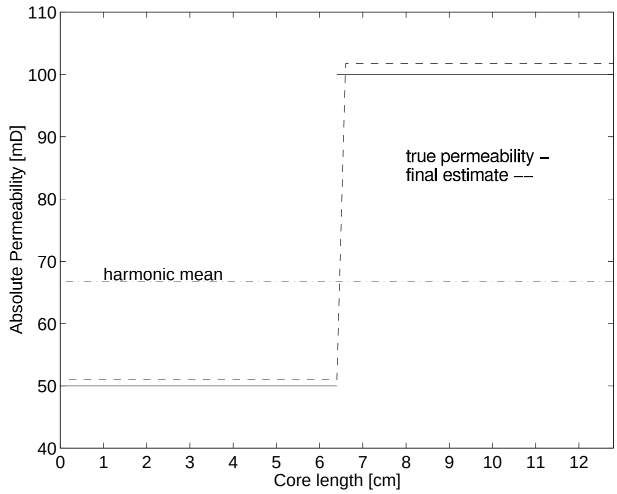

Figure 5: *Estimated and true absolute permeabilities.*

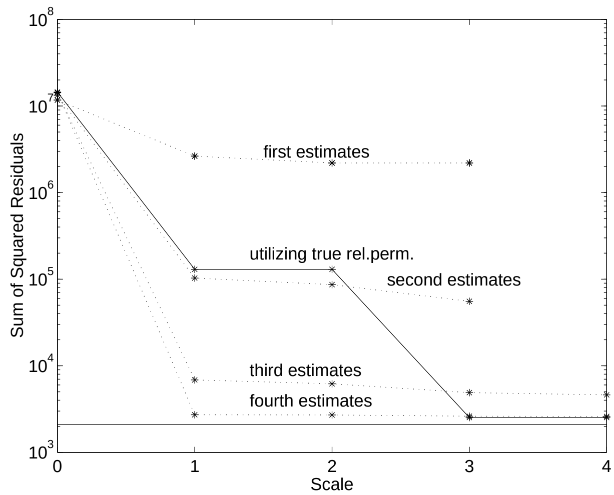

Figure 6: *Sum of squared residuals for the absolute permeability estimates.*

Conclusions.

1. Utilizing the harmonic mean value for the composite core may result in estimated relative permeabilities deviating from the true ones.

2. A method for simultaneous determination of absolute and relative permeabilities has been developed and tested. The method is capable of providing estimates of both the absolute and the relative permeabilities well within the statistical limits.

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