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GAS TRACER TESTS IN AN UNSATURATED FRACTURE: WATER SOLUBLE GASES AS PARTITIONING TRACERS

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ABSTRACT

We demonstrate that hydraulically equivalent models may show striking differences when a gas-migration experiment is performed because of the different correlation between transmissivity, pore volume and entry pressure. We also show that an excellent tool to estimate gas saturation in the fracture is provided by a gas-tracer test, in which a cocktail of gases with different water solubility is employed. These gases behave as partitioning tracers. By comparison of the residence-time distributions of different gases, we are able to compute a streamline effective saturation. The latter is an excellent estimation of the fracture saturation. Moreover, the streamline effective saturation curve contains information, which is useful to identify the conceptual model that more likely applies to the fracture.

INTRODUCTION

In the last years gas tracer tests were performed at the Grimsel underground rock laboratory (Suisse Alps) in addition to traditional solute tests with the aim of better understanding flow and transport in a shear zone (Fierz et al., 2000; Trick et al., 2000; Trick et al., 2001). Briefly, these tests consist of two steps: first a gas is injected in an initially fully-saturated fracture until the gas flow rate at the extraction borehole is almost steady state, then a gas-tracer cocktail is added to the injected gas. The tracer cocktail contains gases with different water solubility, which are expected to experience a different retardation. The tracer retardation also depends on the amount of water available for dissolution, which makes the gases similar to the partitioning tracers normally employed to characterize NAPL and DNAPL distributions in aquifers and reservoirs (see, e.g., Tang, 1995; Jin et al., 1995; Annable et al., 1998; Brooks et al., 2002). We theoretically explore the possibility of using information from gas tracer tests to estimate the fracture saturation and to investigate the pore volume-transmissivity correlation in a single fracture. Indeed, Lunati et al. (2003) demonstrate that discrimination among conceptual models with different pore volume-transmissivity correlations on the basis of classical solute-tracer tests might be impossible except under very favorable conditions – i.e. the integral scale of the transmissivity field has to be known and small compared to the dipole size. Our research is motivated by these results and by the experimental possibilities developed at the Grimsel test site.

GAS TRACER TEST

The first stage of the test consists in a partial de-saturation of the fracture by air injection. Air migration between injection and extraction wells is governed by the highly non-linear equations of two-phase flow and it is simulated by TOUGH2 (Pruess, 1987; Pruess, 1991). Air is injected at a constant mass rate Q in one borehole, while the other borehole is assumed to be open, which means that pressure of both phases is atmospheric (no capillary pressure). When air injection starts, the fracture is fully saturated and the gas phase occupies only the injection borehole. The gas pressure in the borehole rises till it overcomes the entry pressure around the well, then air starts flowing into the formation displacing water. At the beginning only water is produced at the well. Once the gas phase breaks through the extraction borehole, air starts to be recovered and the pressure at the injection borehole drops considerably. After a while the gas-saturation distribution and the velocity field within the fracture can be considered quasi-steady state, i.e. they vary slowly over the typical residence time of air.

From here on, the system is supposed to be in a "frozen" state: both gas-saturation and gas-pressure fields are assumed to be constant in time; gas extraction and gas injection rates are equal and water flow is neglected. At this state, the gas-tracer cocktail is instantaneously added at the recharging well (pulse of tracers) and the concentrations at the producing well are registered as a function of time. This part of the test can be modeled as multi-component transport in a single-phase consisting of a compressible fluid. Indeed, the only effect of the liquid phase is an exchange of tracer mass with the gas phase due to dissolution into water. For these reasons, we simulate the tracer migration by a conventional single-phase modeling package. In order to account for gas compressibility, we solve the pressure equation in p_g^2 by MODFLOW (McDonald and Harbaugh, 1988) and we recalculate the gas-velocity field. An effective porosity is calculated, which accounts for phase saturation and gas-density variations within the fracture. We simulate the tracer-cocktail migration by MT3DMS (Zheng and Wang, 1998). We assume local instantaneous equilibrium between the tracer concentrations in the gas and in the liquid phase. This means that within the cells of the numerical grid, all the water is available for dissolution and reaches the equilibrium concentration stated by Henry's law instantaneously. Under these conditions, the transport of a soluble gas can be modeled as the transport of a linearly retarded tracer. Since it depends on the saturation, the retardation coefficient of the tracer *i* is space dependent and given by

$$R_i = 1 + \frac{1 - S_g}{S_g}\gamma_i \,, \qquad (1)$$

where the solubility factor γ_i depends linearly on the temperature and on Henry's constant of the tracer. We consider an ideal tracer (id) and two soluble tracers, i.e. xenon, Xe, and hydrogen sulfide, H_2S. The retardation coefficients of the two soluble tracers are plotted in Figure 1 as a function of gas saturation.

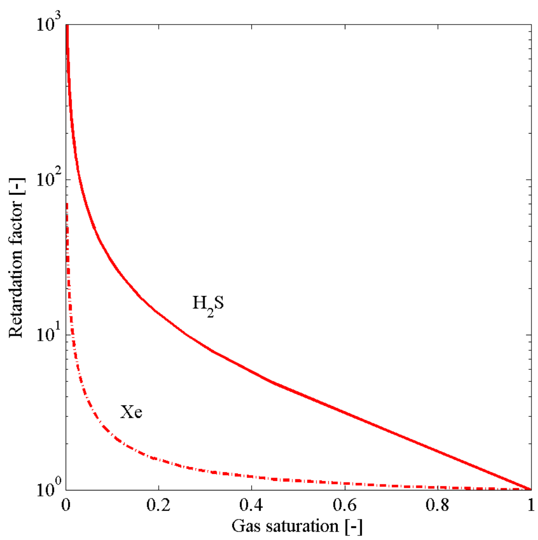

Figure 1. Retardation coefficients for the two water-soluble tracers (Xe, H_2S) as a function of gas saturation.

The main idea of our analysis is to obtain an estimation of gas saturation by calculating the retardation coefficients according to equation (1). The tracer breakthrough curve at the extraction well, $C_i(t)$, represents the residence-time distribution of the tracer *i*, whereas the mass-recovery curve, $MR_i(t)$, is the cumulative probability function of the residence time. From the residence-time distribution of the tracers is then possible to compute a streamline-dependent retardation factor by identifying each streamline via the mass recovery at its arrival time. Indeed, since the mass recovery is a monotonically increasing function, it can be inverted and we write

$$R_i(MR) = \frac{t_i(MR)}{t_{id}(MR)} \,. \qquad (2)$$

Writing equation (2), we assume that the arrival order of the streamlines is the same for different. In other words, it assumes that streamlines cannot overtake each other due to the retardation factor experienced by soluble tracers. Since the retardation factor is a monotonically decreasing function of the gas saturation (Figure 1), this assumption is justified also in heterogeneous saturation fields, because the saturation is the highest in the most permeable regions. Inserting equation (2) into equation (1) we can compute a streamline-effective saturation by solving for S_g. We obtain that the streamline-effective saturation is the harmonic mean (weighted by the inverse of the velocity) of the gas saturation along the streamline, i.e.

$$S_g(MR) = \left\{ \frac{\int_{MR} \left[S_g(s)u(s)\right]^{-1} \mathrm{d}s}{\int_{MR} \left[u(s)\right]^{-1} \mathrm{d}s} \right\}^{-1} \,. \qquad (3)$$

THREE SIMPLIFIED CONCEPTUAL MODELS

Following the criterion that a model has to be as simple as possible, we focus our attention on three different fractures, which correspond to very intuitive and simplified models: a rough-walled fracture filled with a homogeneous fault-gouge, a rough-walled empty fracture and parallel-plate fracture filled with a heterogeneous fault-gouge.

In a 2D model, the hydraulic properties of a fracture are fully described by the integral over the depth of hydraulic conductivity *K*, i.e. the transmissivity *T*. The three conceptual models described above naturally imply a different relationship between transmissivity and pore-volume fields (Lunati et al., 2003): in the parallel plate model both fields are uncorrelated (uncorrelated model, UM), whereas in the rough-walled filled fracture they are perfectly correlated (completely correlated model, CCM). These two cases represent two extremes between which the empty fracture is an intermediate situation (partially correlated model, PCM).

For comparability reasons we require that the three models have the same transmissivity field (hydraulically equivalent models) and the same total pore volume. We also assume the same capillary model (Brooks-Corey) with the same λ-parameter (λ=1.5), but a different entry pressure distribution. Indeed, on the basis of microscopic considerations the entry pressure, p_d, can be related to the conductivity K via Leverett's model, i.e. $p_d \sim K^{-1/2}$. This relationship implies that the correlation between pore volume and transmissivity tends to smooth the distribution of the gas-phase, because it reduces the correlation between transmissivity and entry pressure. When the pore volume-transmissivity correlation is perfect (homogeneous fault gouge), the entry pressure becomes constant in space. In contrast, if the fault gouge is heterogeneous (UM) or the rough-walled fracture is empty (PCM), the entry pressure is space dependent, which we expect to yield an unevenly distributed gas phase.

RESULTS

The numerical simulations are performed in synthetically generated single fractures. We consider an ensemble of lognormal transmissivity fields with mean value $\langle \log T \rangle = -9.7$ and variance $\sigma_{\log T} = 1.18$. The correlation function is exponential and has integral scale $I = 0.033L$, where L is the linear dimension of the domain. The latter is a square with horizontal surface $A=L^2$ discretized into 101×101 blocks. No-flow boundary conditions are imposed on the four sides, and a dipole of size $L/2$ is placed in the middle of the domain. The ensemble consists of 7 realizations. The limited number of realizations is a consequence of the high variance, which yields very time-expensive numerical simulations. For all realizations, three different fractures are constructed according to the conceptual models and to the comparability criteria presented in the previous section and a gas tracer test is simulated.

The numerical simulations show that gas flow takes place only in few discrete channels characterized by very high gas saturation and separated by fully water-saturated regions, if the UM is adopted. Striking differences are noticeable compared to the CCM, which produces a continuously distributed gas phase. The PCM is in between, showing a pattern similar to the UM, but characterized by a smaller variability of the saturation: extreme values are smoothed out by the partial correlation between pore volume and transmissivity, which in turn decreases the correlation between entry pressure and transmissivity. In Figure 2 the quasi-steady gas-saturation distribution is shown for one realization in which the streamlines collapse into a single channel (shortcut). In contrast, the CCM still yields a gas flow that takes place in a more spread-out region where the gas saturation is considerably smaller than in the channels produced by the other two models.

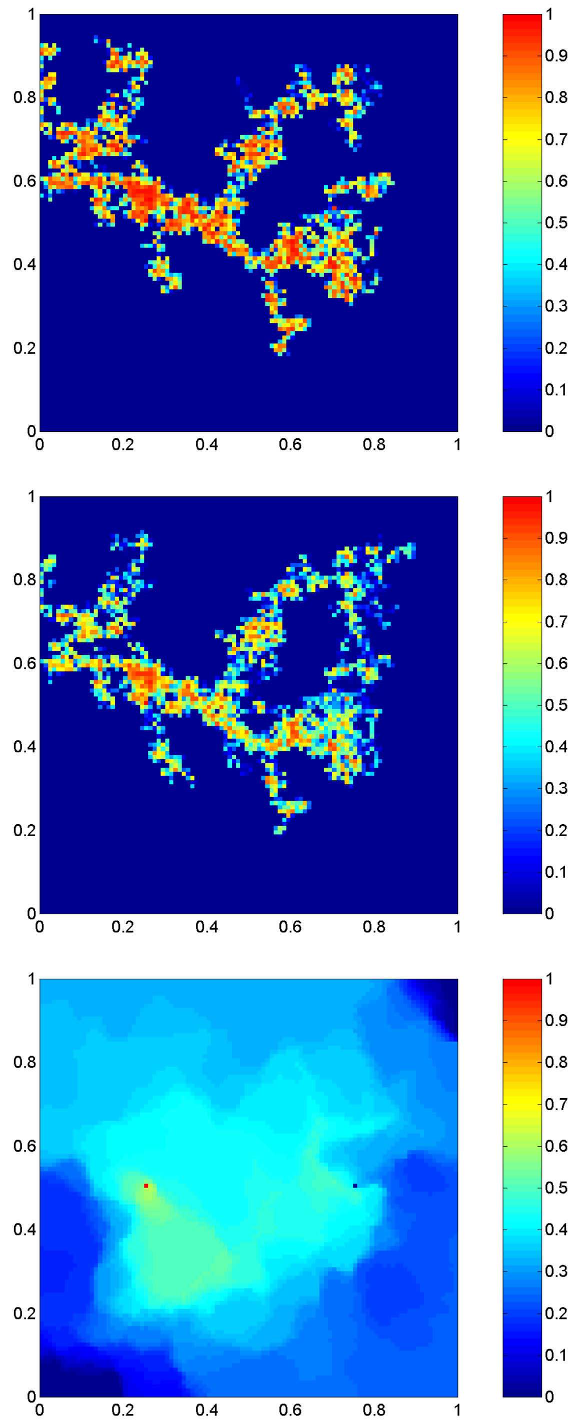

Figure 2. Quasi steady-state gas saturation distribution for different pore volume-transmissivity correlation models (from top to bottom: UM, PCM, CCM).

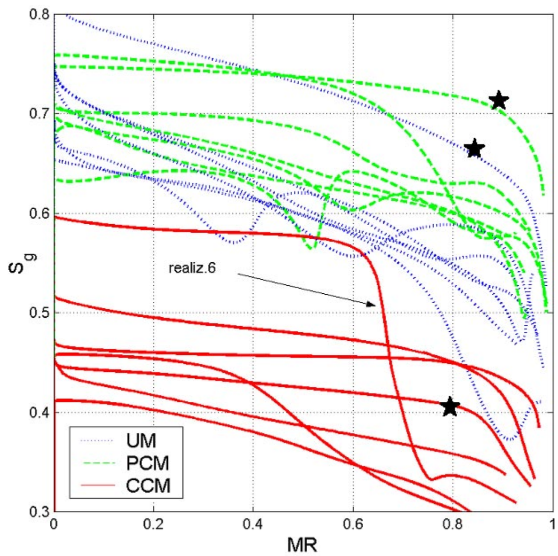

Figure 3. Effective gas saturation as a function of mass recovery at the extraction well for different pore volume-transmissivity correlation models and realizations. Data from hydrogen sulfide are used.

The streamline effective saturation computed according to equations (1) and (2) is plotted in Figure 3 for all models and different realizations. The retardation of hydrogen sulfide is used. This picture definitely demonstrates the capability of estimating the fracture saturation by gas tracer tests, since it clearly proves that in the UM and PCM flow takes place in region with higher gas saturation than in the CCM. (The curves labeled with a star correspond to the three gas-saturation distributions of Figure 2.) Most realizations produce a non-monotonic saturation curve when the UM or the PCM is adopted, which clearly proves the presence of well-separated channels. Indeed a channel represent a cluster of streamlines in which gas saturation exhibits a long stream-wise correlation and a short correlation in direction perpendicular to the flow. If more than one channel exist and they are well separated, contributions of different channels to mass recovery do not overlap. Each maximum of the gas saturation curve represents the contribution of a different channel; a minimum represents the contribution of the slowest, less gas-saturated streamlines of the channel before the contribution of the fastest, more gas-saturated streamlines of the next channel comes. If the pressure field determines gas-saturation distribution, as in the CCM, the correlation in the direction transversal to the flow direction is large. This makes it unlikely, even in very heterogeneous fields, that a streamline might breakthrough at the extraction borehole before other streamlines, which have higher gas saturation. Indeed, streamlines with similar length have also similar gas saturation because of the long transversal correlation length. This yields a monotonically decreasing saturation curve.

As additional example of the efficiency of a gas tracer test in estimating saturation in the fracture, we consider realization 6 (see Figure 3). In case the CCM is adopted, the streamline effective saturation curve indicates the presence of two well-distinct regions with a very different saturation: a large amount of tracer (around 60%) is traveling to the extraction well in a highly gas-saturated region (S_g=0.6), the rest comes to the well in a region with a gas saturation around 35%. That is exactly what happens in the fracture as it can be observed in Figure 4, which shows the gas-saturation distribution in realization 6 when the CCM is adopted.

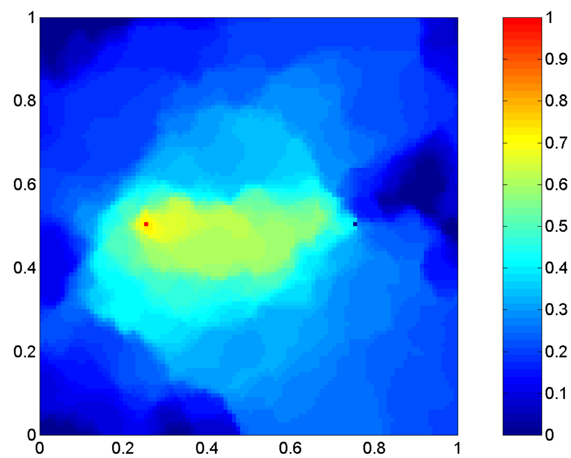

Figure 4. Quasi steady-state gas distribution for realization 6 when the CCM is adopted.

CONCLUSIONS

The conceptual model adopted for the pore volume-transmissivity correlation has a strong effect on the saturation of the fracture via the entry pressure, which can be related to the transmissivity in a different way according to the different conceptual models. Due to Leverett's model, a correlation between pore volume and transmissivity tends to smooth the distribution of the gas-phase, because it reduces the correlation between transmissivity and entry pressure. In the UM and in the PCM the streamlines collapse into few channels characterized by very high gas saturation and separated by water saturated regions inaccessible to gas flow. In contrast, the CCM yields a gas flow that still takes place in a more spread-out region where the gas saturation is considerably smaller than in the channels produced by the other two models.

These differences in the saturation can be very well observed by means of a gas tracer test in which at least two tracers with different water-solubility are employed. We demonstrate that this technique provides an excellent tool to estimate the fracture saturation by computing a streamline-averaged saturation. The tracers dissolve into the water phase according to their solubility, which is known, and to the amount of water available. By comparing the residence-time distribution of two tracers we can compute a streamline retardation factor, from which we can extrapolate a streamline effective saturation.

This technique also provides additional information to that obtained by classical tracer tests and helps to discriminate among the conceptual models: a non-monotonically decreasing curve of the streamline effective saturation as a function of mass recovery clearly proves the presence of well-separated channels within the fracture, which is normally observed in the UM or PCM. This behaviour, which is produced by a long stream-wise correlation of the gas saturation, is not expected in the CCM. In extreme cases in which only a channel is present (shortcut) the UM and PCM also produce a monotonic streamline saturation curve, but differences from the CCM can be observed as the arrival-time distribution is less dispersed. This is due to the fact that flow in a channel is similar to mono-dimensional flow, whereas the CCM always produces a completely two-dimensional flow, because of the smoother and more spread-out saturation distribution.

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