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# Phase invasion in a fracture shear zone: Analysis with Macro Modified Invasion Percolation

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An alternative conceptual model for phase invasion based on modifications of invasion percolation is formulated and applied to model gas invasion from an injection well to a withdrawal well within an initially water saturated, fracture shear zone. In the Macro Modified Invasion Percolation model, phase growth is determined by variable capillary forces in combination with gravity and first order viscous forces (embodied in a simple single phase viscous dipole solution). Results of a parametric study demonstrate the relative influences of capillary force variability, Bond number, and Capillary number on withdrawal well capture and the intervening phase structure.

## 1. INTRODUCTION

Two-phase flow and transport within fractured rock remains an enigma. Limitations of traditional conceptual models based on porous continuum formulations with either composite, dual porosity, or dual permeability approaches have become more apparent as the questions we ask about the system increase in sophistication. While the treatment of fractures, fracture zones, and matrix as discrete may be better, the porous continuum formulation remains limited both physically (incorporating fingering, fragmentation and pulsation is problematic) and computationally (a large number of nodes are required to resolve even a two dimensional problem of limited extent). As an alternative, let us consider a modeling approach based on Macro Modified Invasion Percolation (MMIP). MMIP represents the physics of phase displacement at a given node scale with a set of rules and then connects nodes into networks on which the phase invasion problem is simulated. The objective of such a model is to obtain the phase structure as it evolves during the displacement process. This structure influences many important processes such as fracture-matrix interaction (e.g., phase, solutes, reaction), and transport/dispersion of constituents within each phase (e.g., solutes, colloids, gases).

In recent years, Invasion Percolation (IP), as introduced by Wilkinson and Willemsen [1], has been successfully modified (MIP) for a variety of situations to better reflect the underlying physics of the invasion process. Meakin et al. [2] included gravity for nonwetting invasion and Glass and Yarrington [2] included both gravity and the interfacial smoothing mechanism provided by multiple-adjacent-neck-pore-filling facilitation required for wetting invasion. Other forms of MIP have been proposed to accommodate a variety of additional processes including gas diffusion during drying [4] and film flow during wetting [5], as well as application to rough walled fractures [6-8] and the inclusion of viscous forces [9-11]. Additionally, forms of MIP have been up-scaled to model phase displacements within heterogeneous aquifers under gravity destabilized [12] and gravity-stabilized situations [13-14].

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In this paper, MMIP is formulate and applied to the example problem of gas invasion from an injection borehole to a withdrawal borehole within an initially water saturated formation containing a discrete planar, fracture shear zone. Such a configuration is similar to that of a test designed and conducted at the Grimsel Test Site in Switzerland over the past several years. First order average viscous forces in addition to gravity and spatially variable capillarity are included in the model. Simulations help to illustrate system response as a function of the controlling dimensionless parameters.

## 2. MODEL FORMULATION

Consider a thin, planar fracture shear zone within which gas is injected from one borehole and water withdrawn from a second. Employing the MMIP approach presented in Glass et al. [11-12], the planar fracture zone is covered by a three dimensional (3D) network of blocks, each of which has a threshold pressure that must be achieved to span the individual block. This block threshold spanning pressure ($P_t$) is composed of three parts including capillary ($P_c$), gravity ($P_g$), and viscous pressures ($P_v$). Working with dimensionless variables (denoted by hats) we have:

$$\hat{P}_t = -\hat{P}_c + B\hat{z} + Ca\hat{P}_v$$

where $B$ is the dimensionless Bond number weighing gravity to capillary forces, $Ca$ is the dimensionless capillary number weighting viscous to capillary forces:

$$B = \frac{\Delta\rho g \cos(\theta)\delta\langle R\rangle}{2\sigma|\cos(a)|}$$

$$Ca = \frac{\langle R\rangle \mu_w Q}{2\sigma|\cos(a)|4\pi k b}$$

and

$$\hat{P}_t = \frac{P_t\langle R\rangle}{2\sigma|\cos(a)|}, \quad \hat{P}_c = \frac{sign(\cos\alpha)}{\hat{R}}, \quad \hat{R} = \frac{R}{\langle R\rangle}, \quad \hat{x} = \frac{x}{\delta}, \quad \hat{z} = \frac{z}{\delta},$$

with $<R>$ the representative value (~ mean) for the threshold radius ($R$) field, $\sigma$ the interfacial tension, $a$ the contact angle at the fluid-fluid-solid interface, $\delta$ the representative length scale taken as the block size, $\Delta\rho$ the density difference between phases ($\rho_{gas}$-$\rho_{water}$), $g$ the gravitational acceleration, $\theta$ is the angle of the shear zone from the vertical, $\mu_w$ the viscosity of the water, $Q$ the flow imposed by the dipole, $k$ the effective permeability, $b$ the thickness of the fracture zone, and ($x$,$z$) the Cartesian coordinates with $z$ increasing upward.

The dimensionless pressure field is taken to first order as the base single phase flow solution for a homogeneous medium which for the case of an injection-withdrawal dipole is taken as:

$$\hat{P}_v = \ln\left[\frac{(\hat{x}-\hat{x}_w)^2 + (\hat{z}-\hat{z}_w)^2}{(\hat{x}+\hat{x}_w)^2 + (\hat{z}-\hat{z}_w)^2}\right]$$

where wells are located at ($-\hat{x}_w,\hat{z}_w$) and ($\hat{x}_w,\hat{z}_w$).

Once the threshold spanning pressure is calculated for all blocks in the domain, phase growth is simulated by an IP algorithm that invades blocks with lowest spanning pressure while maintaining connection through the invading phase to its source. Thus, phase invasion begins from the injection well. Blocks connected to the well are searched to find and invade the block with the lowest threshold spanning pressure. This growth opens new choices for the invasion process, which once again chooses the block with the lowest spanning pressure to invade, and so on.

## 3. MODEL APPLICATION AND QUALITATIVE BEHAVIOR

The MMIP model is applied on a domain composed of a 500 $\delta$ tall by 750 $\delta$ wide by 10 $\delta$ thick fracture shear zone discritized with cubic blocks of sides $\delta$ ($3.75(10)^6$ blocks). The algorithm is implemented with orthogonal connectivity so that each block is connected to the surrounding 6 in the 3D network and phase trapping is not implemented. Gas invasion commences from a box 7 by 7 by 10 $\delta$ centered at the injection well location and halts when an identical box around the withdrawal well is contacted.

The $R$ field is taken as spatially uncorrelated with distribution given by a beta function defined over the range [$R_{min}$, $R_{max}$]:

$$f(R) = \frac{(\alpha + \beta + 1)}{\alpha!\beta!(R_{\max} - R_{\min})^{\alpha+\beta+1}}(R - R_{\min})^{\alpha}(R - R_{\max})^{\beta}$$

where $\alpha$ and $\beta$ are integers greater than –1. Here only symmetrical distributions are considered ($\alpha$=$\beta$) with values of 0, 4 and 32 to consider the influence of distribution narrowing (see Figure 1, left). Ten different 3D $R$ field hierarchies were realized. A single 2D realization is shown in Figure 1(right).

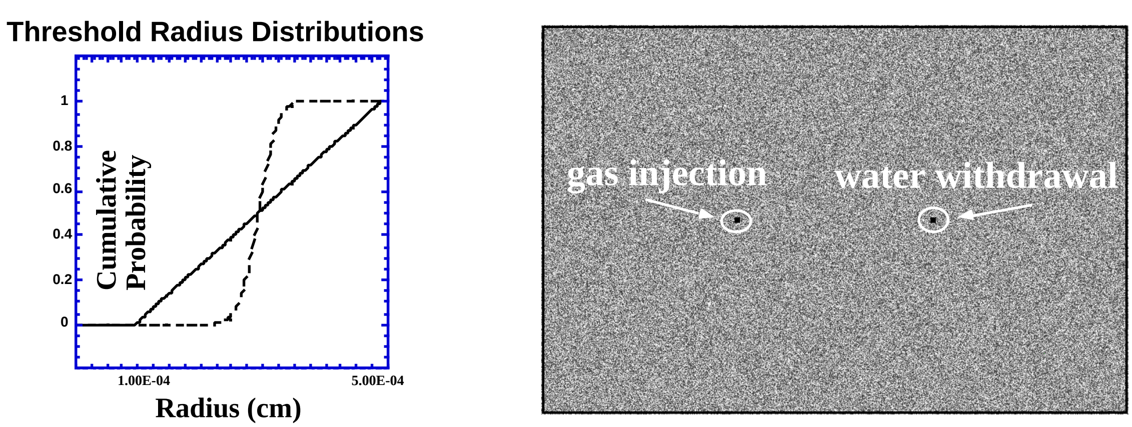


Figure 1: $R$ distributions for $\alpha = \beta$ of 0 and 32 (left) and $R$ field with gas injection and water withdrawal wells separated by 250 $\delta$ (right).

A baseline case was selected comparable to the Grimsel Test Site dipole experiment with $\langle R \rangle$ taken as 0.0003 cm within the $R$ range [0.0001, 0.0005] cm, $\sigma$ as 72 dynes/cm$^2$, $a$ as 180 degrees (gas fully nonwetting), $\theta$ as 0 degrees (vertical), $\Delta\rho$ as 1.0 g/cm$^3$ (air and water), and $\delta$ as 1 cm yielding a fracture zone 10 cm thick with wells separated by 2.5 meters. Simulations were conducted for each $R$ field with the baseline $B$ multiplied by 0, 0.125, 0.25, 0.5, and 1.0 to simulate shear zone orientation between horizontal and vertical. At each of these orientations, *Ca* was varied across the series 0, 1, 2, 4, 16, 32, 64, 256 and 1024. To facilitate qualitative comparison, Figures 2-5 show simulation results for a single 3D *R* field hierarchy realization.

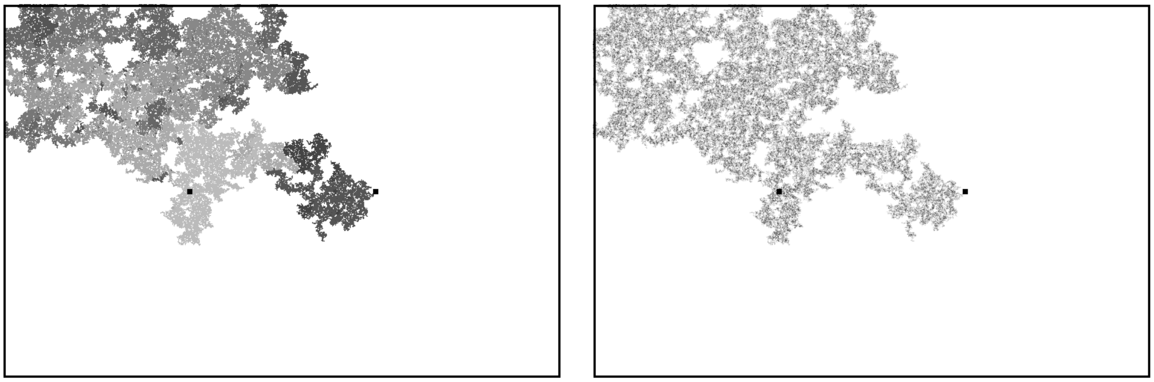

Figure 2: Invasion order (left) and final thickness averaged saturation field (right) for $B = 0$ and $Ca = 0$. Both invasion order and saturation are given by gray scale with light to dark representing increasing values.

Results for $B = 0$ and $Ca = 0$ conform to IP with the invasion order and final saturation fields independent of the *R* distribution (see Figure 2). Average saturation within the invaded region shown in the figure is ~0.2 and the complicated ramified phase structure is fractal. Across realizations, gas phase often contacts the external boundaries of the problem before the withdrawal well and thus would not have been captured. We note that the complicated structure and transport pathway at withdrawal well contact will significantly influence transport within the gas phase.

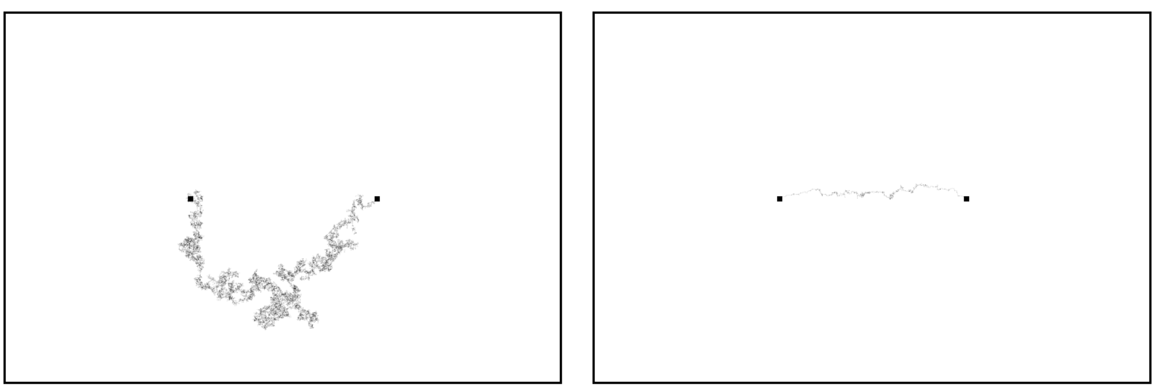

Figure 3: Final thickness averaged saturation fields for $\alpha = \beta = 0$ and $B = 0$ with $Ca = 16$ (left) and 1024 (right).

Results for $B = 0$ with $Ca > 1$ show that in most cases, at $Ca = 1$, the withdrawal well captures the gas before it hits the problem boundaries. As *Ca* increases beyond 1, complication of the gas phase structure decreases and the route from injection to withdrawal becomes more direct (see Figure 3).

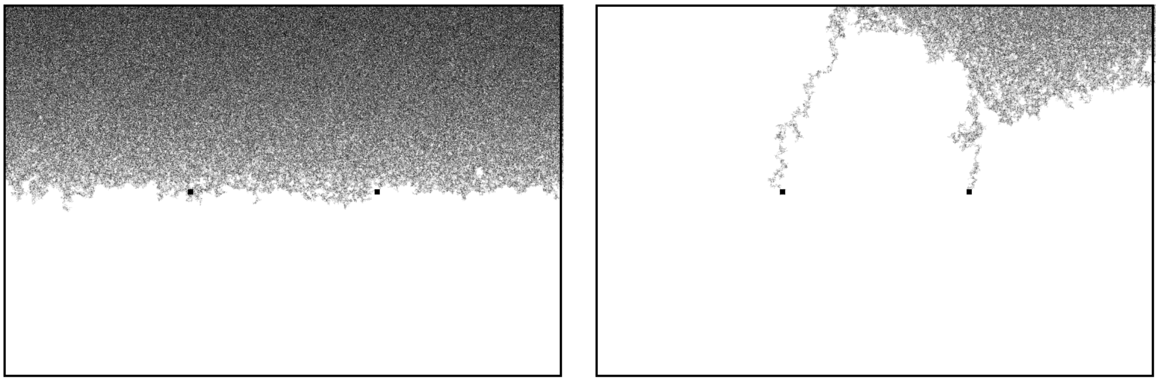

Figure 4: Final thickness averaged saturation fields for $\alpha = \beta = 0$ and *B factor* = 1 with *Ca* = 0 (left) and 64 (right).

For increasing *B* at *Ca* = 0, a buoyant finger moves upward to the top boundary and then back fills the domain downward (Figure 4, left). As *Ca* is increased, increasing *B* shifts capture at the withdrawal well upward in *Ca* such that at *B factor* = 1, capture first occurs without filling the top half plane at *Ca* of 64 (Figure 4, right).

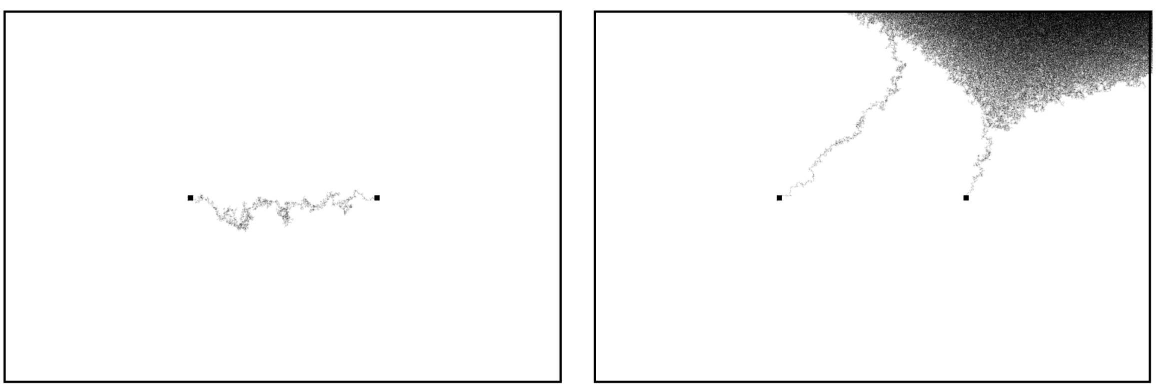

Figure 5: Final thickness averaged saturation fields for $\alpha = \beta = 32$ with *B* = 0 and *Ca* = 16 (left) and *B factor* = 1 and *Ca* = 64 (right).

Finally, when the *R* distribution is narrowed, the influence of variable capillary forces is decreased relative to gravity and viscous forces and causes a shift toward lower *B* and *Ca* behavior. Such a shift has also been demonstrated by Glass and Yarrington [3] with respect to the simulation of gravity driven fingers.

## 4. CONCLUDING REMARKS

Gas phase structure as a function of interacting capillary, gravity and viscous forces has been modeled above the characteristic scale $\delta$ using a Macro Modified Invasion Percolation approach. The model yields behavior that coincides qualitatively with expected system behavior. These results and companion work within individual fractures, discrete fracture networks, and granular porous media, suggests the increasing efficacy of MIP approaches to model the structure of evolving two-phase flows.

With respect to the design of dipole gas invasion tests that will increase understanding of two phase flow and transport within the gas phase, MMIP simulation results underscore the importance of carefully considering *R* distribution as well as *B* and *Ca* as their interplay greatly influences capture by the withdrawal well and the intervening structure of the transport pathway.

Obvious extensions to this work include consideration of:

- spatially correlated fields, especially across the thickness in the context of shear zones
- evolving first order viscous influence
- second order viscous forces that can capture the multiple and braided nature of viscous fingering at high *Ca*
- pulsation and fragmentation within the phase structure
- gas compressibility issues

Finally, comparison of MMIP approaches to those conceptualized within the context of traditional and nontraditional porous continuum as well as to experiments both in the field and in the lab would be of great interest.

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