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# Formation Damage and Impact on Gas Flow Caused by Biofilms Growing Within Proppant Packing Used in Hydraulic Fracturing

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## Abstract

Formation damage as a result of hydraulic fracturing of unconventional gas reservoirs is known to occur by many speculated processes such as: filter cakes on fracture faces, matrix swelling, cleat plugging, gel damage and water blocking. In low permeability matrices, capillary forces can also prevent effective dewatering and result in water blocking of gas flow. Another type of formation damage that may be qualitatively understood but not quantified is the impact of biofilms. This paper combines two micro-scale modeling techniques to evaluate and predict the effects of biofilms on proppant packed fractures in unconventional gas reservoirs. Both a two phase flow model for gas and liquid and a modern cellular automaton biofilm model were combined to simulate the impact on gas flow rates in biofouled propped fractures. Initial simulations of just two phase flow without biofilms but varied proppant surface wettabilities, indicated that hydrophobic proppant surfaces provide better dewatering than hydrophilic surfaces. Gas flow rates dropped in half when biofilms were added to the model at a pore volume of approximately 10%. In addition, further modeling indicated even the same biofilm volume but different distribution within grains and pore-throats can impact gas flow rates as much as 10%. It is hoped that this work will help hydraulic fracturing engineers improve their fracture designs and subsequent treatments to maximize gas flow rates from their assets.

## 1. Introduction

Exploration and production of unconventional reservoirs are increasing as conventional hydrocarbon resources begin to deplete. Many of the well mapped and identified unconventional resources are land based making these resource plays more attractive because they are less expensive to develop and operate. Frequent hurricanes in the Gulf of Mexico and the damaging impact on production platforms also help justify more stable land based assets. Technology advances and operational experience have allowed for the economic development of unconventional gas resources. Improvements in horizontal well drilling and “slick water” hydraulic fracturing are two of the technologies that have enabled the successful development of unconventional gas resources in North America.

Gas production rates from stimulated wells are one of the main performance metrics for successful development and operation of shale gas reservoirs. Typical initial production rates from shale gas wells can range from 4-8 MMcf/d. Also typical are production decline curves that seem to asymptote anywhere from 6 months to a year. Many parameters control these production rates including: initial gas in place and associated reservoir porosity/permeability characteristics, effectiveness of horizontal well placement, stimulation technology used and associated fracture propping agents (Cipolla et al., 2009; Palisch et al., 2008). In addition, the chemical additives and physical processes used to drill, complete and stimulate unconventional gas wells in low permeability formations are also known to cause subsequent formation damage. Such damage includes: filter cakes on fracture faces, matrix swelling, cleat plugging, gel damage and water blocking. In low permeability matrices, capillary forces can also prevent effective dewatering and result in water blocking of gas flow. The use of surfactants, microemulsions and even alcohols has been used to help remove water trapped by capillary forces (Penny et al., 2006; Zelenev and Ellena, 2009). Even with chemical assisted water removal technologies, significant water can remain trapped in very low permeability matrix rock, preventing maximum gas recovery rates.

Another type of formation damage that may be qualitatively understood but not quantified is the impact of biofilms. Biofilms are formed by a community of microorganisms growing attached to a surface (Stoodley et al., 2002b). The surface can be a solid substratum or even an interface such as an oil/water interface. The physical structures called biofilms created by the microorganisms can be considered a "gel" or non-Newtonian fluids (Klapper et al., 2002; Stoodley et al., 2002a). Biofilms are essentially 98% water but stabilized in the form of a gel. The typical chemical or enzymatic approaches used to breakdown natural gels used during hydraulic fracturing will not be effective at destroying biofilms because the bio-polymers and their adhesion forces are more complex than natural gelling agents (Flemming et al., 2007; Mayer et al., 1999). Biofilms are also dynamic structures that grow and accrete as well as disperse cells to find new colonization sites. The impact microorganisms have on reservoir porosity and permeability is well known in the petroleum industry and has been harnessed for Microbial Enhanced Oil Recovery (Pintelon et al. 2009). This paper will quantify the mechanisms and impact of biofilm on formation damage principally occurring within propped fractures.

## 2. Microscale Modeling of Two Phase Flow and Biofilms

Unconventional tight gas reservoirs are characterized by a network of fractures on the order of a centimeter thick and several kilometers in length. Fractures are filled by proppants that prevent the collapse and allow for fast gas recovery. A fracture filled by proppants can be considered as an artificial porous media and the gas-water flow behavior can be then investigated at the pore scale. One of the most important variables on two-phase flow transport in porous media is capillary pressure. The capillary pressure is a property of a pair of fluids and the porous media. Thus it is related to the fluid-fluid interfacial tension, to the wettability, and to the geometry of the porous media, such as pore throat and pore void sizes and the connection between them.

Common approaches to simulate flow of two immiscible fluids at the pore-scale are the pore network models and the Lattice-Boltzmann techniques. The pore network models represent the porous media by a pore throat and pore bodies of simple geometric shapes (spheres, triangles and cylinders). Difficulties are encountered in establishing the appropriate shapes, size, locations, connections and orientations of the pores and throats. However, once constructed, network models are capable of simulating flow phenomena by constructing rules or by solving flow equations in simplified geometries (Reeves and Celia, 1996; Held and Celia, 2001; Joekar-Niasar et al. 2008). The Lattice-Boltzmann method is a discrete velocity model constructed on a discrete lattice that approximates the incompressible Navier-Stokes equation at each lattice point. In this method the kinetic equation and boundary conditions are imposed locally. At the pore scale only several approaches have been developed to investigate biofilm growth in porous media (Kapellos et al., 2007; Knutson et al, 2005) and permeability reduction in porous media induced by biofilm growth (Pintelon et al. 2009). Modeling the effect of biofilms on solute transport was also addressed frequently (e.g., Chen et al., 1994; Wanner et al, 1995).

At the macroscale or reservoir scale, several models have been developed to describe microbial growth, transport and processes involved in microbial enhanced oil recovery, and to predict permeability modification that results from microbial activity in porous media (Zhang et al. 1992; Desouky et al. 1996; Behesht et al., 2008). To date, models describing two-phase flow behavior and the presence of bacteria colonies together at the pore scale are not available. In this study, flow of immiscible fluids is combined with the biofilms at the pore scale, to investigate the effect of bacteria colonies on the gas flow behavior. A relatively new method, Phase Field (Anderson et al. 1998), is used to track the moving interface between two immiscible fluids (gas-water) and a particle-based method is employed to generate bacteria colonies growing in the complex geometry constituting the porous medium.

## 3. Model description

Two main steps can be distinguished in this model approach. First the bacteria are attached to the grains and they are allowed to grow only in water supplied with nutrients. The whole domain is water-saturated and the biofilm grows in the pores, on the grains. This process may take days to weeks. In a second step, the gas starts to flow in the model domain displacing water ("dewatering phase"). This is a much faster process than biofilm growth, in the scale of seconds for the small domain computationally considered. Therefore, we compute separately the development of the biofilm on grains, and we apply the obtained structures (grain-biofilm geometry) as input for the dewatering model.

### 3.1. Model geometry

A horizontal fracture in a tight gas reservoir is modeled in a simplified rectangular domain of 1cm height by 5 cm length. The distribution of solid grains (proppant material) on which the biofilm can develop is generated in a random fashion given a certain allowed interval of circular grain sizes (from 1 to 2 mm in diameter) and a fixed minimum pore throat size (100 μm).

### 3.2. Two-phase flow equations

For the dewatering model, the transport of mass and momentum is described by the Navier-Stokes equations (1) and (2) assuming that both fluids (the gas and the liquid phase) are incompressible:

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot \left[ -p\mathbf{I} + \eta\left(\nabla \mathbf{u} + \left(\nabla \mathbf{u}\right)^T\right)\right] + \mathbf{F} \tag{1}$$

$$\nabla \cdot \mathbf{u} = 0 \tag{2}$$

In equations (1) and (2), ρ denotes an average fluid density (kg/m$^3$), η is the average dynamic viscosity (Pa·s), **u** represents the velocity (m/s) , *p* denotes the pressure (Pa). The capillary pressure is incorporated in the Navier-Stokes equation as source term by adding the surface tension force **F**, function of the phase field parameter ϕ and surface tension σ (N/m). The phase field method does not directly track the interface between two fluids, but instead, the interfacial layer is governed by a phase field variable ϕ. The dimensionless phase field ϕ is defined such that the volume fraction of the components of the fluid are (1+ϕ)/2 and (1-ϕ)/2. The surface tension force is added to the Navier-Stokes equations as a body force. The evolution of the phase field variable is governed by the Cahn-Hilliard equation, which is a 4th-order PDE, implemented in the software package COMSOL Multiphysics (COMSOL, 2008). The average fluid properties are computed from the volumetric fractions of gas and liquid. Thus, the average fluid density is $\rho = \rho_G + (\rho_L - \rho_G)\varepsilon_L$ and the corresponding average fluid viscosity is $\eta = \eta_G + (\eta_L - \eta_G)\varepsilon_L$. The liquid fraction $\varepsilon_L$ is defined as a function of the phase field parameter ϕ (see COMSOL, 2008).

The two-phase flow was driven by the pressure difference between the inlet and outlet domain boundaries. Regularly, this pressure difference was set to 1000 Pa per 5 cm (corresponding to cca. 200 bar/km fracture), but different other simulations examined the effect of pressure on the obtained gas flow rates. On the top and bottom boundaries (rock surface) as well as at the proppant grain's surface, wetted wall boundary conditions were used. This takes into account the contact angle $\theta$ between fluids interface and the walls (COMSOL, 2008).

### 3.3. Bacteria attachment and biofilm development

In the past decades several methods to model biofilms growth have been developed. These approaches can be subdivided into three main groups: continuum biofilm models (Dockery and Klapper, 2001; Eberl et al., 2001; Alpkvist and Klapper, 2007), discrete biomass-based models on a grid (Kapellos et al., 2007; Picioreanu et al., 1998; Pizarro et al., 2001), discrete gridless particle-based models (Kreft et al., 2001; Picioreanu et al, 2004; Xavier et al, 2005). In this study a discrete cellular automaton model as described in Picioreanu et al (1998).

The bacteria were first attached to the grains at random positions. The biomass was represented in a regular square grid. When the biomass concentration in a square grid element reached a certain critical value, it was allowed to divide and push other biomass-filled grid elements according to a cellular automaton algorithm. The result is formation of round shaped biofilm colonies attached to the grains. The geometry of the colonies was then imported into the two-phase model. The contour of each colony was then considered to be a wall boundary under the assumption that neither gas nor convective water flow could penetrate the biofilms.

## 4. Model solution

The model equations were solved sequentially, in a MATLAB-driven algorithm (MATLAB 2008b, Mathworks, Nattick Massachusets). The MATLAB code called not only solvers from COMSOL for the time-dependent two-phase (COMSOL, 2008). In a second step, the gas flow equations, but also own Java-written algorithms for the biofilm model. Details on the model solution will be presented apart in a forthcoming publication in the model domain displaces water.

## 5. Results and discussion

Physical properties of water and gas phases, as well as surface tension and contact angles used in the simulations are listed in Table1.

**Table 1. Physical properties of fluids chosen as for air/water system**

| Property | Value | Unit |
|---|---|---|
| Density gas, $\rho_G$ | 1.2 | kg/m$^3$ |
| Density water, $\rho_L$ | 1000 | kg/m$^3$ |
| Viscosity gas, $\eta_G$ | $1.5\times10^{-5}$ | Pa.s |
| Viscosity water, $\eta_L$ | $10^{-3}$ | Pa.s |
| Contact angle fluids-grains (hydrophilic), $\theta_1$ | $1.5\times\pi/4$ | rad |
| Contact angle fluids-grains (hydrophobic), $\theta_2$ | $1.2\times\pi/2$ | rad |
| Contact angle fluids-biofilms, $\theta_3$ | $1.1\times\pi/4$ | rad |
| Interfacial tension, $\sigma$ | 0.07 | N/m |

One of the variables that plays a role on the flow and transport of immiscible fluids at the pore scale is the capillary pressure. Capillary pressure is related to the fluid-fluid interfacial tension, to the geometry of the porous media, to the wettability and thus to the contact angle formed between the grain surface and the fluid-fluid interface.

To establish how wettability can affect the gas flow behavior, two types of simulations were carried out. First the proppants were considered as hydrophilic, i.e., the contact angle $\theta_1$ was assigned as input parameter at the grain surface. Then a second simulation was performed with a contact angle $\theta_2$ such that the proppant surface was hydrophobic. Figure 1 shows the ratio between the total volume of water in the domain and the total pore volume versus time. Initially the domain was fully saturated with water (ratio=1). Then the water is displaced as the gas phase flows into the pores and the ratio of water falls below 1. For a hydrophilic proppant there is a certain ratio of residual water (here ~0.35 from the total pore volume) that cannot be further displaced by gas flow. However, it can be noticed from Figure 1 that in case of hydrophobic proppants less water is trapped within the pores and the fraction of water decreases below 0.1.

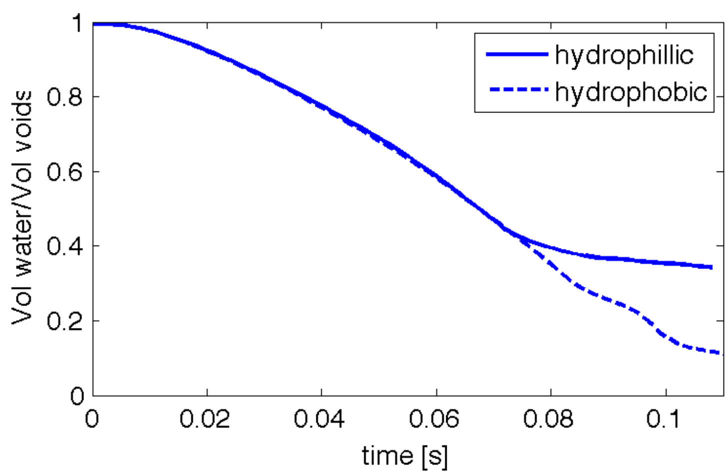


**Figure 1 Volume of water over the total pore volume of the model domain in case of wettable (hydrophilic case) or non-wettable (hydrophobic) porous media**

The presence of bacteria colonies can affect the gas flow in at least two ways: (1) by modifying the wettability of the grains or (2) by changing the geometry of the porous media (both porosity ratio and pore throat sizes). Two microbial colonies can grow on adjacent grains and merge together, occluding the pore space or the pore throat. A decrease of pore throat size implies an increase in the pressure drop along the porous medium. Consequently, only when gas pressure exceeds the capillary pressure, will gas be allowed to flow through the pore space. If the capillary pressure is higher than the gas-entry pressure, then gas will not flow into the pores and water will be trapped. A series of simulations were performed to study the effect of biofilms on gas flow. Bacterial colonies retain more water than the proppant grains, thus they are more wettable. This is reflected in the contact angle $\theta_3$ (listed in Table 1) assigned as describe a wettable surface of bacteria colonies.

Figure 2 represents the gas flow (in red) through a porous medium at three different time steps $t_1$=0.03 s, $t_2$=0.07 s, $t_3$=0.108 s. First the pore voids were fully saturated by water (in blue) then the gas phase flowed in from the left side displacing water. Figure 2 compares the gas flow in the absence of biofilms (left panels) with the flow in the presence of biofilms (right panels: biofilm colonies attached to the grains are shown as grey areas).

Water and gas flow rates calculated in absence of biofilms were compared with the values obtained from the simulations carried out with biofilm grown on the proppants (Figure 3). Note that to avoid boundary effects, the instantaneous flow rates are calculated close to the middle of the simulated domain at x=0.03 m. The percentage of biomass in the domain was 10% and the total porosity was reduced from 65 % to 55% when biofilms were included. It can first be noticed that with biofilms the gas front passes the x=0.03m limit later than in the absence of biofilms (Figure 3 – left). This is due to the reduction in driving force for the gas flow (i.e., larger pressure drop when biofilms grow in the medium). Secondly, after 0.1s the gas flow rate in presence of biofilms is only half of that calculated with the non-clogged porous medium (compared in Figure 3 – left, the reduction in gas flow rate from $6\times10^{-3}$ to $3\times10^{-3}$ $m^3/s$). Biofilms can also trap water in the porous medium. Figure 3 (right) shows the volume of water related to the total pore volume versus time. Initially, the domain is fully water saturated (water saturation = 1) and the saturation decreases when the gas moves into the domain. After a quasi-steady state has been reached in the two-phase flow, 30 and 40% of water remained trapped within the pore space. In this specific configuration, little difference is observed on the water saturation when the bacteria colonies are present.

The spatial distribution of the bacteria colonies in the domain also plays an important role in the resulting gas flow. Figure 4 shows the results of two simulations performed with identical total porosity of 58% and the biomass fraction of 8.4% (cases named *Colony A* and *Colony B*). These two simulations differed only in the spatial arrangement of the biomass. The gas flow rate of $3\times10^{-3}$ $m^3/s$ in the case of the *Colony B* is reduced to only $1\times10^{-3}$ $m^3/s$ in the simulation with *Colony A*. Thus, although porosity and biomass fractions are the same for both simulations a significant difference on the gas flow rate can be noticed. Bacteria in *Colony B* simulation clogged some pore throats forcing the gas to flow in a preferential channel at higher velocity. Moreover, 10% more water remained trapped in the pore voids for Colony *B* (see Figure 4 - right). This case study emphasizes two points. First, it is important to carry out a careful statistical treatment of the simulation results. In order to obtain reliable results, several simulations must be run and results averaged. This also questions the validity of the size for the “representative volume element” chosen in this modeling study. Second, the simulations point to the necessity to describe the porous medium characteristics not only in terms of global variables (e.g., void fraction or porosity, biomass hold-up, etc.), but also in terms of pore size distributions.

## 6. Summary and Conclusions

Phase field method and Navier-Stokes equations were adopted to describe the two-phase flow behavior in a porous media with and without biofilms, taking into account different material wettabilities. Bacteria colonies (biofilms) were included in the two-phase model and considered as a wettable surface, with a wettability higher than normal proppant grains. In a first model approach without biofilm, wettabilities of proppant grain surfaces were varied (i.e. hydrophilic versus hydrophobic). These model simulations demonstrated the importance of contact angle properties on dewatering of propped fracture voids. Hydrophobic proppant surfaces provided more complete dewatering than hydrophilic, 0.1 compared to 0.35 residual pore volume.

In the presence of 10% biofilm volume the gas flow rates were reduced to half. Moreover, the distribution of biofilm on grains (at the same biofilm volume fraction) also affects the gas flow rate because of differential change in the medium tortuosity and flow patterns. This effect points to the importance of understanding how any remedial treatments that remove biofouling from porous media may re-distribute the biovolume and thus impact production flow rates. In addition, numerical simulations showed that the presence of bacteria can increase the water trapping compared with the case biofilm-free porous medium.

This work will help petroleum engineers involved with designing, monitoring and managing hydraulic fracturing applications used in unconventional gas exploration maximize their assets. Proper water management and microbial control strategies will help minimize the effects described in this study and maximize gas production rates.

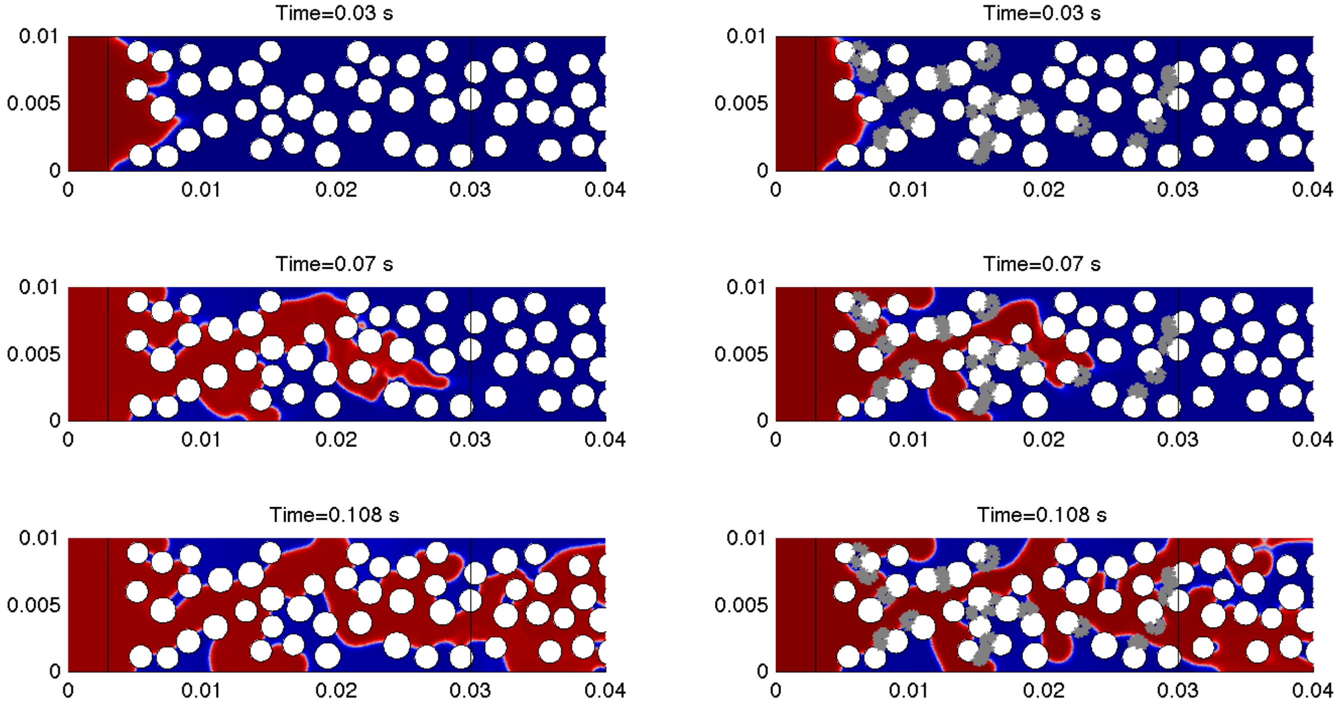


**Figure 2. Simulated displacement of the water phase (in blue) by the gas phase (in red) at three different time steps in porous media: (left) without biofilms and (right) with biofilms (shown as grey areas).**

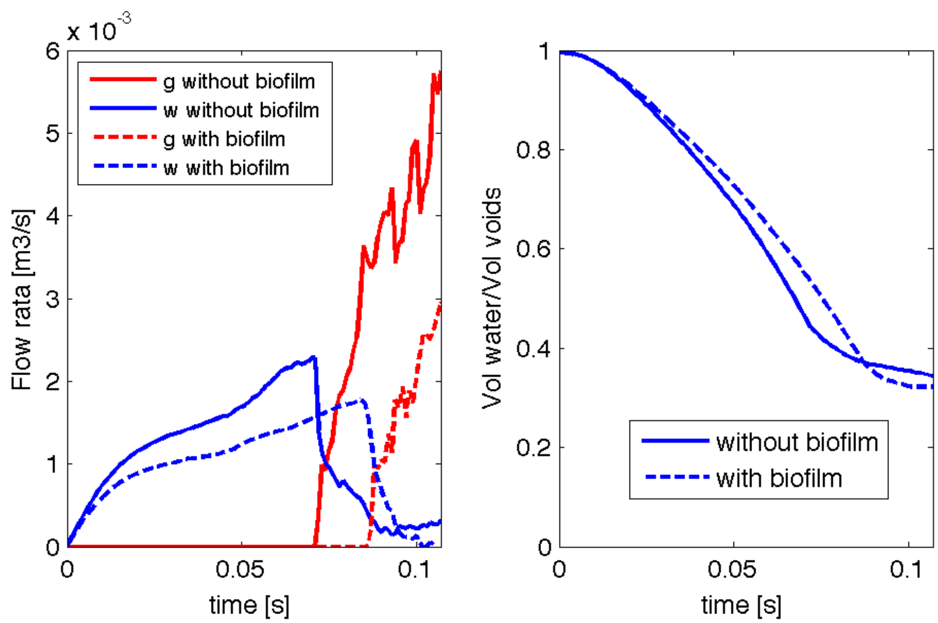


**Figure 3. Left panel: Water and gas flow rate versus time passing the x=0.03 m line, in a domain with (dashed lines) and without (solid lines) biofilms. Right panel: Water saturation versus time in a simulation with and without biofilm developed on the proppants.**

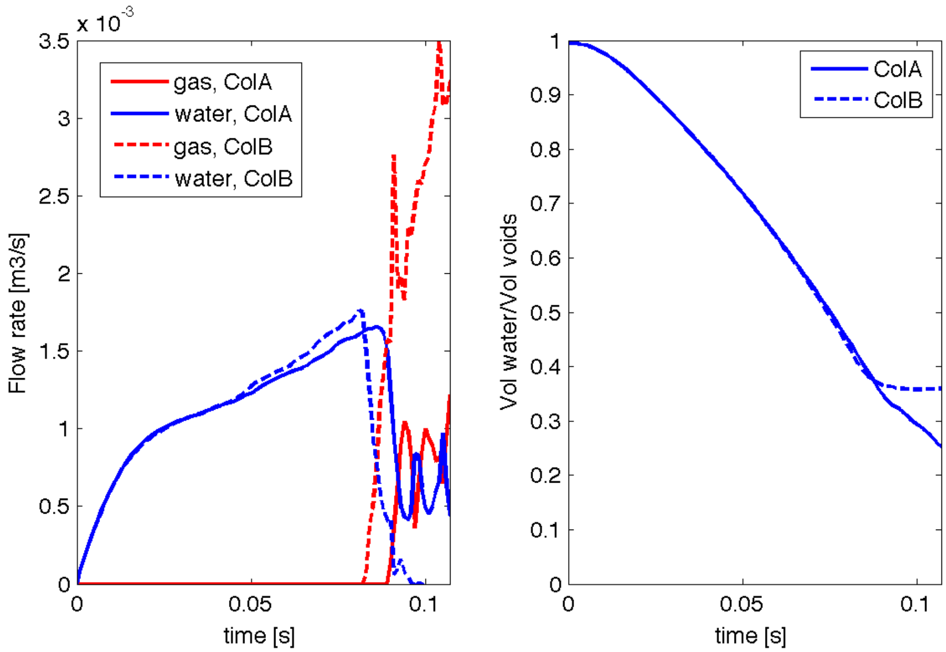


**Figure 4 Left: gas and water flow rate for simulated cases with biofilm in porous medium - colonies A and B have the same pore fraction and the same biomass fraction, but different biomass spatial distribution. Right: water trapped within the pore voids in the simulation cases Colonies A and Colonies B.**

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