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MODELING WELL STIMULATION THROUGH ACID INJECTION

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ABSTRACT

We develop a model for the spreading of reacting liquid injected into a permeable rock. We examine reactions which lead to either precipitation and a decrease in permeability or dissolution and an increase in permeability. We focus on the case in which there is a density difference between the host reservoir fluid and the injected liquid. We illustrate the evolution of the shape of the reacting zone for a constant injection rate, and identify how the location of the leading edge of the injected liquid advances ahead of the reacted zone.

INTRODUCTION

Commercial exploitation of many geothermal systems is limited owing to mineral precipitation and the associated decrease in permeability of the system. This inhibits liquid flow and associated mining of heat from the system. One solution to this problem involves the injection of a reacting fluid into a number of the wells, designed to dissolve the precipitate, increase the permeability and hence stimulate the reservoir. However, the path followed by such liquid and the evolution of the reaction zone is very complex. In particular, for pressure driven flow, the interface between the reacted and unreacted rock becomes morphologically unstable, and breaks down into a series of dissolution veins. As a result, the permeability is enhanced only in a fraction of the rock, and the injected liquid tends to follow these veins to an extraction well along the veins, bypassing much of the reservoir (Phillips, 1991; Hinch and Bhatt, 1993; Ortoleva et al., 1986).

In many such systems, the density of the injected fluid will be somewhat different from the host fluid, owing to different chemical composition of the fluids. As the liquid spreads from the injection well, the gravitational forces associated with this difference in density begin to dominate the force associated with the applied pressure at the source well. Eventually, the flow becomes controlled by the gravitational forces (e.g. Woods, 1999), and this leads to considerable differences in the morphology and rate of spreading of the reaction front compared to purely pressure driven flow.

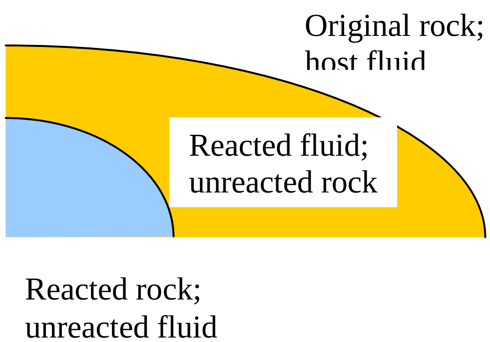
We now develop a simple mathematical model to examine how the morphology of the reacting interfaceand the spatial distribution of the injected liquid evolve with time. Knowledge of the difference between the position of the leading edge of the reaction front and of the injected liquid is very important for interpreting tracer studies designed to follow the reaction front.

THE MODEL

As shown in figure 1, we model the system in which the injected fluid has a density $\Delta\rho$ in excess of the host fluid in the reservoir, and in which the reaction leads to a change in the permeability of the reservoir from k_1 to k_2 such that

$K = k_1/k_2$

Figure 1 – schematic of the spreading front of injected liquid (acid) and of the reaction front produced by this liquid. The reaction is assumed to change the permeability of the rock



We also assume that the reaction front is relatively sharp so that that effects of reaction kinetics are very rapid compared to the time-scale of the flow. Hence we may model the speed of the reaction front as having value λ u where u is the Darcy velocity of the fluid. Here $\lambda(1-\phi)$ represents the volume of rock that reacts with a volume $(1-\lambda)\,\phi$ of the reacting liquid.

Since we assume the dynamics of the current is controlled by the gravitational force associated with the density difference between the host fluid and the injected acidic fluid, the reaction zone and the injected fluid will run along the lower boundary of the reservoir, as shown in figure 1 schematically.

When the current is long and thin, the vertical pressure gradient will be dominantly hydrostatic and so the equations governing the flow are given by

$$\mathrm{p} = \mathrm{p_o}(y) + g\Delta\rho(h_l + h_u - y)$$

$$Q_l = -h_l \frac{k_l}{\mu}\frac{\partial p}{\partial x} \quad ; \quad Q_u = -h_u \frac{k_u}{\mu}\frac{\partial p}{\partial x}$$

$$\frac{\partial h_l}{\partial t} = -\lambda \frac{\partial Q_l}{\partial x} \quad ; \quad \frac{\partial h_u}{\partial t} = -(1-\lambda)\frac{\partial Q_l}{\partial x} - \frac{\partial Q_u}{\partial x}$$

The first equation represents the hydrostatic pressure gradient in the flow, associated with the density difference $\Delta\rho$. The depth of the reaction zone is $h_l(x)$ and of the layer of reaction liquid above this is $h_u(x)$. The second pair of equations represents the horizontal flux of fluid in the reacted rock (ie below the reaction front) and in the reacted liquid (i.e above the reaction front). The third line of equations represents the conservation of mass in the zone of reacted rock and the reacted liquid. These equations implicitly incorporate the small vertical velocities associated with the spreading and slumping flow by allowing the depth of the different regions to evolve with time as a result of the horizontal gradient of the horizontal flux along the lower boundary. In the model we set the porosity of the system, $\phi = 1$, for simplicity of notation, without any loss of generality.

The equations may be combined to form two coupled non linear equations

$$\frac{\partial h_l}{\partial t} = \lambda k_l S \frac{\partial}{\partial x}\left(h_l \frac{\partial H}{\partial x} \right)$$

$$\frac{\partial H}{\partial t} = k_u S \frac{\partial}{\partial x}\left[\left(H + \left(1 - \frac{k_l}{k_u} \right) h_l \right) \frac{\partial H}{\partial x} \right]$$

and for a constant injection rate, these equations admit a class of shape-preserving (similarity) solution in one-dimension, in which the current spreads and thins along the lower boundary of the domain.

$$h_l = At^{1/3} f_l\left(\frac{x}{Bt^{2/3}} \right)$$

$$H = At^{1/3} f_H\left(\frac{x}{Bt^{2/3}} \right)$$

In this solution, the functions f_l and f_h represent the shape of the reaction front and of the leading edge of the injected liquid which drives the reaction. The form of the solution depends critically on the two parameters K and λ as may be deduced from the non-linear diffusion equations at the bottom of the previous page.

We have solved the non-linear equations to find the similarity solutions of the form shown above. Three types of solution emerge.

Precipitation solutions K>1

If we have a precipitation reaction, leading to an increase in permeability, the reaction front remains close to the injection site, and the reacted fluid runs far ahead of the reaction front as it moves from the very low permeability reacted rock which develops by the injection well and into the original, high permeability rock, as shown in figure 2.

Dissolution solutions K<1

If the reaction leads to dissolution of the rock, then the injected fluid tends to run rapidly through the high permeability reacted zone before moving across the reaction front into the low permeability host rock. As a result of the greater density of the injected fluid, this leads to formation of a long narrow reaction zone along the lower boundary of the reservoir, as shown in figure 3.

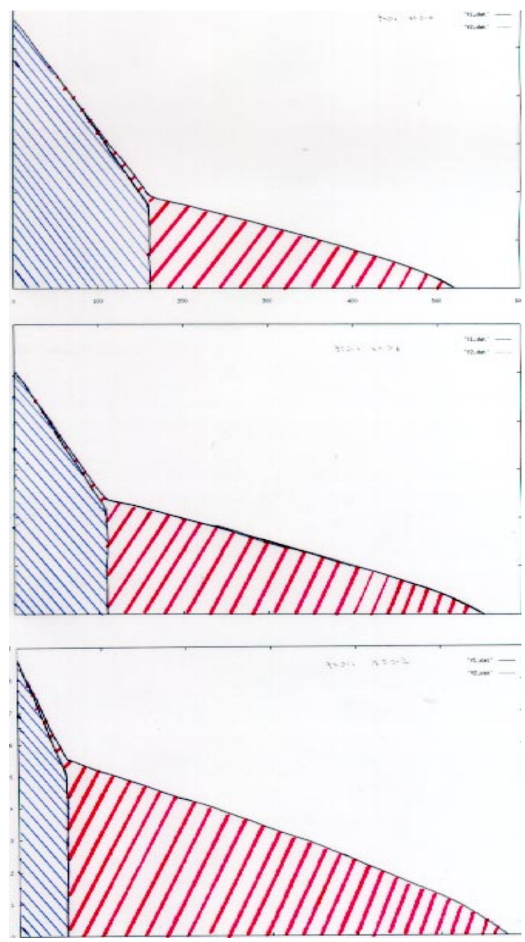


Figure 2 : morphology of the reaction zone and the location of the injected liquid for three precipitation reaction calculations. Here K=0.1 and λ =

In the case that $K\lambda < 1$, the reaction zone does not extend to the nose of the current essentially because the change in premeability is relatively small or the volume of fluid required to react with a given volume of rock is very large. In the case $K\lambda < 1$, the reaction zone does extend to the leading edge of the current.

The difference between such strong and weak dissolution reactions may have important implications for the interpretation of tracer monitoring as a mechanism of following reaction fronts formed by liquid injection.

Figure 3 Structure of reaction front produced in strong dissolution reaction. In these calculations, the reaction zone extends all the way to the front of the region occupied by injected liquid. Numbers on the curves represent different values of λ. Here K=10..

CONCLUSION

We have developed a simple mathematical method to track the propagation of reaction fronts and to gain insight into the effectiveness of acid injection as a well stimulation technique. A key result is the prediction of a gravity driven reaction zone, in which the reacted fluid collects above and ahead of the zone of reacted rock, with the relative positions of the region filled with reacted fluid and the reacted rock depending on the reaction parameter λ and the change in permeability due to the reaction K

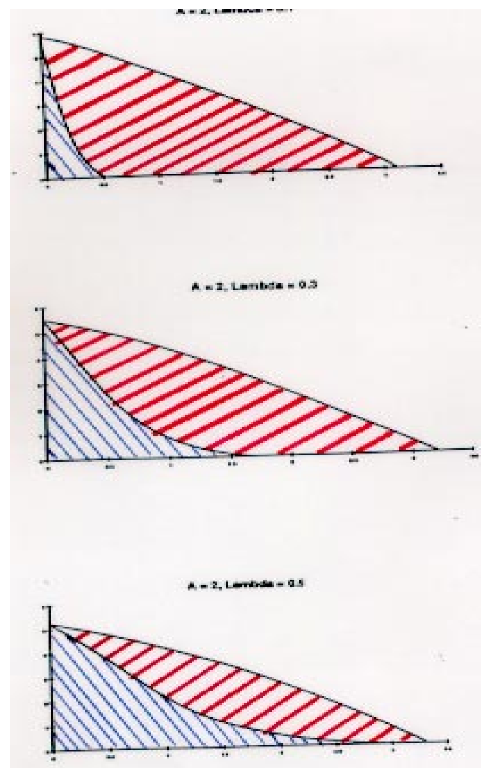


Figure 4 Structure of reaction front in weak dissolution reaction, in which the reaction zone lags the injected fluid front, owing to either a large volume of liquid required per unit mass of reacted rock or owing to a small change in permeability resulting from the reaction. Here K=2.

REFERENCES

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