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CHARACTERIZATION and MODIFICATION of FLUID CONDUCTIVITY in
HETEROGENEOUS RESERVOIRS to IMPROVE SWEEP EFFICIENCY

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Principal Investigator: H. Scott Fogler

Project Manager: Robert E. Lemmon

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SUMMARY OF TECHNICAL PROGRESS

I. Introduction

Work performed during this quarter was aimed at investigating the behavior of foamed gel using our newly developed model. Three porous medium and gel properties were systematically varied to determine their effect on the foamed gel breakdown process; The pore throat size distribution standard deviation, σ , was varied to investigate the effect of microscopic heterogeneities. Three different rupture pressure relationships (RPR) were used to simulate gels with different yield functionalities. Two different deformation constant relationships (DCR) were used to study gel elasticity. The variance between runs with different properties was adequately revealed using a 10 by 10 network; thus larger networks were avoided and computational effort saved. The pore throat and lens dimensions were assigned to the network via random sampling of a normal distribution. The maximum and minimum bond diameters were the mean bond size, plus or minus three standard deviations, respectively. A mean lens length and standard deviation of $1e^{-4}$ m, and $3e^{-6}$ m, were used in every run. A narrow lens size distribution was used in absence of a relationship between lens length and pore throat diameter. Furthermore, foamed gel heterogeneity could be simulated easily by varying the pore throat size distribution against the narrow lens length distribution. *This technical progress report will discuss only one of the interesting results found during our modeling investigation, the effect of gel elasticity on foamed gel breakdown.*

There are three important characteristics of a foamed gel breakdown curve, illustrated in Figure 1; 1) The pressure required to break the foamed gel bank (the percolation rupture pressure, point A) marks the onset of conductivity. 2) The slope of the

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ascending portion (point B) of the breakdown curves, immediately following percolation, indicates the permeability response to inlet face pressure increases. 3) The plateau permeability ratio (post-rupture permeability, point C) is the maximum permeability possible. Disregard the plateau permeability ratio values presented here because they are a function of the resistance factor relationship (RFR) which we have not yet developed.

Figure 1. Foamed gel breakdown curve. Point A corresponds to breakthrough of first conductive channel. B is during the rupture stage, where the conductive network of channels grows. C is the post-rupture permeability, after most of the gelled lenses have ruptured.

Two types of gel were simulated. One was an elastic gel, whose properties we determined from our laboratory investigations using a polyacrylamide gel based foaming solution. The other was a hypothetical rigid gel. The rigid gel was assumed to have the same ultimate strength as the elastic gel, i.e., a rigid gelled lens with a specific aspect ratio would rupture at the same applied stress as an elastic gelled lens with the same aspect ratio. The effect of the gel elasticity on foamed gel breakdown is shown in Figure 2. The rigid foam percolation rupture pressure is less than that for elastic foamed gel; and the increase in network permeability with pressure is more gradual for the rigid foamed gel. The distinction between foams comprised of rigid lenses and elastic lenses is best illustrated by examining the effect of network length on the change in the percolation rupture pressure and the fraction of ruptured lenses at percolation. Figure 3 reveals that the percolation rupture pressure increases linearly with network length for elastic gels and remains constant for rigid gels. Figure 4 shows that the fraction of ruptured bonds at percolation is always greater for rigid foams. This result suggests that a straighter less branched pathway develops in elastic foamed gels.

Figure 2. Effect of the lens deformation constant relationship on the breakdown of foamed gel. The rupture pressure relationship is the experimental data fit.

Figure 3. Effect of network length on percolation rupture pressure

Figure 4. Effect of network length on fraction of ruptured bonds at percolation.

Examination of the breakdown phenomenon revealed the important role of lens deformation on foam breakdown behavior. Elastic lenses deform when a stress is applied. Deformed lenses compress downstream trapped gas bubbles, transmitting pressure to downstream lenses. As a result of downstream lens deformation, the percolation rupture pressure is related to the total force a series of lenses can withstand. Thus, many individually weak lenses can support a large applied force. Also, the pressure transmission

makes it possible that interior lenses may rupture first and initiate the sudden formation of a conductive pathway at the percolation rupture pressure. Rigid foamed gel does not benefit from the cooperative effect of deforming lenses (no pressure transmission), and thus breakdown proceeds in an invasion percolation-like manner where the weakest bonds along the foamed gel-injected fluid interface rupture; and the pressure required to break through a rigid foamed gel bank is equal to the strongest lens along the path of least resistance. The impact of this difference is realized in designing a foamed gel plug from different gel systems. If the gel system is elastic, the strength or resistance of the plug to rupturing is proportional to its length. On the other hand, a rigid foamed gel system's resistance to rupture is related to the strength of the individual lenses, and independent of the foam bank length.

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