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A Comparison of Different Types of Blocking Agents

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ABSTRACT

Many different materials have been proposed to reduce channeling of fluids through fractures and streaks of very high permeability. These materials include gels, particulates, precipitates, microorganisms, foams and emulsions. In this paper, we compare the placement and permeability reduction properties of these different types of blocking agents. Comparisons were made of their selectivity in entering high-permeability rock in preference to low-permeability rock. We also examined their ability to reduce permeability to a greater extent in high-permeability, water-saturated zones than in low-permeability, oil-saturated zones. Concepts are identified that may lead to blocking agents with placement and/or permeability-reduction properties that are superior to those of gels.

INTRODUCTION

In oil recovery operations, several different types of processes have been proposed to reduce channeling of fluids through fractures and streaks of very high permeability in reservoirs. Processes that use crosslinked polymers or other types of gels have been most common. However, processes using foams, emulsions, suspended solids, microorganisms, and precipitates (or other products of phase transitions) have also been proposed. In this paper, we compare the effectiveness of these different types of blocking agents. This paper summarizes the results from extensive literature surveys and analytical and numerical analyses that we performed over the past three years.[1-3]

Our analyses focused on the placement characteristics and permeability-reduction properties of the blocking agents. Ideally, a fluid-diversion process should reduce channeling of fluids through high-permeability, watered-out flow paths without damaging oil productivity. However, in most applications, the blocking agents penetrate to some extent into low-permeability, oil-productive zones. Oil production can be either enhanced or retarded, depending on how the blocking agent's performance in low-permeability rock compares with that in the "thief" zone.[4-6]

The amount by which a process reduces the flow capacity of a given zone depends on at least three factors: (1) the distance of penetration of the blocking agent, (2) the permeability reduction provided by the blocking agent, and (3) the flow geometry. We used theoretical and numerical analyses to quantify how selective the various agents are in entering high- vs. low-permeability rock. We also investigated which blocking agents have the best permeability-reduction characteristics—that is, those that reduce permeability to a greater extent in high-permeability, water-saturated zones than in low-permeability, oil-saturated zones. We also considered whether different types of blocking agents can be combined to perform better than either agent individually. For example, can a gelant be combined in a synergistic way with a foam or a particulate to provide superior fluid diversion?

For each of the materials discussed in this paper, a large body of literature exists. Because of space limitations, most of these publications will not be cited here. However, many of these papers and patents are discussed in Refs. 1-3. Much of the literature makes unsubstantiated claims that materials will selectively enter and block high-permeability, watered-out zones in preference to less-permeable, oil-productive zones. Critical analyses of these claims reveal that most of the proposed schemes suffer from the same placement limitations that gels experience.[1-3] In this paper, we focus on those concepts that may allow the development of blocking agents with placement and/or permeability-reduction properties that are superior to those of gels.

GELS

Placement. In this work, gelants and gels are used as standards against which other materials are compared. Typically, gelants consist of an aqueous solution with one or more reactive components (e.g., a polymer and a crosslinker). The gelant components react to form an immobile gel. The distance of gelant penetration into a given zone can be quantified by straightforward applications of the Darcy equation and fractional-flow theory. These calculations demonstrate that gelants can penetrate to a significant degree into all open zones—not just those zones with high water saturations.[4,5] If precautions (such as zone isolation) are not taken during gelant placement in unfractured wells (i.e., radial flow), low-permeability zones can be seriously damaged even in extremely heterogeneous reservoirs.[4] An effective gel placement is much easier to achieve in fractured wells than in unfractured wells because of the fracture's linear flow geometry and because of the large permeability contrast between the fracture and the porous rock.[4-6] Theoretical developments[4-7] and many field results[8-10] indicate that gel treatments are most effective in reservoirs where fractures constitute the source of a severe fluid channeling problem.

For the different types of blocking agents, Table 1 compares the selectivities in entering high- versus low-permeability zones. Each entry in Table 1 lists the distance of penetration (in linear flow) of the blocking agent into one zone relative to the distance of penetration into an adjacent zone that is 10 times more permeable. Water injection is assumed to result in a unit-mobility displacement in this example. For each material, one case allows no crossflow between layers, while a second case permits free crossflow between the layers. The basis of these calculations can be found in Refs. 1-4 and 11. The values in Table 1 are meant to illustrate what could happen (i.e., the extremes of behavior)—not necessarily what will happen in every case.

Table 1. Comparison of Placement Properties in a Two-Layer Linear System with a 1:10 Permeability Contrast

BLOCKING AGENT	distance in low-k zone ÷ distance in high-k zone	
	without crossflow	with crossflow
GELANTS		
1. low viscosity	0.10	0.10
2. high viscosity	0.32	0.99
PARTICULATES		
3. small particles	0.10	0.10
4. intermediate-sized particles	0.00	0.00
GELANT WITH PARTICLES		
5. small particles	0.10	0.10
6. intermediate-sized particles	0.01	0.01
7. large particles	0.99	0.99
8. IN SITU PRECIPITATES	0.10	0.10
FOAMS		
9. no foam forms in low-k zone	0.00	0.00
10. foam forms in both zones	0.99	0.99
11. GELANT WITH FOAM	0.99	0.99
12. DILUTE EMULSIONS	0.12	0.20

For the base case of a gelant with a water-like viscosity (Data Row 1 in Table 1), the distance of penetration into the low-permeability zone is 10% of that in the high-permeability zone (both with and without crossflow[4,11]). Increased gelant viscosity increases the relative distance of penetration into the less-permeable zone. If crossflow cannot occur between layers, the relative distance of penetration for viscous fluids is governed by the square root of the permeability ratio for the two zones.[4] Thus, in Table 1 (Data Column 1, Data Row 2), the value for high-viscosity gelants is $\sqrt{0.1}$ or 0.32. If fluids can freely crossflow between zones, the distance of penetration of a viscous gelant into a low-permeability zone can be almost as great as that in an adjacent high-permeability zone[11,12] (see Data Column 2 of Data Row 2 in Table 1).

For a given distance of gelant penetration into a high-permeability stratum, the minimum penetration into a less-permeable zone is achieved using a gelant with a water-like viscosity or mobility.[4,5] In unfractured wells, viscous non-Newtonian gelants will not provide a placement that is superior to that for a water-like gelant.[13] Therefore, in our work, the placement properties of a water-like gelant are used as a basis for comparison while investigating the placement properties of other materials. The other values in Table 1 will be discussed in subsequent sections.

Permeability Reduction. The permeability-reduction properties of gels depend on whether they are "strong" or "weak" gels. Strong gels (i.e., gels that fill most or all of the aqueous pore space in a porous medium) reduce the permeability of different porous rocks to approximately the same value (in the low microdarcy range).[14,15] In one sense, this behavior could be very desirable. All gel-contacted portions of a heterogeneous reservoir could be altered to have nearly the same permeability. However, for most strong gels, the final permeability is so low that flow is effectively stopped[15] (unless the distance of gel penetration into the rock is very small[6,7]).

For "weak" or "thin" gels (i.e., those leaving a significant permeability), residual resistance factors generally decrease with increasing rock permeability (i.e., flow through low-permeability rock is restricted by a greater factor than in high-permeability rock). Tracer studies indicate that these gels occupy a small fraction of the pore space.[15] Weak gels usually result from incomplete gelation and the formation of a small volume of gel aggregates.[15-17] For unbuffered gelants, gel aggregates are usually formed in an uncontrolled manner, so they provide low to intermediate residual resistance factors that are often difficult to predict from one porous rock to the next.[15] In some cases, a more controlled permeability reduction can be achieved using polymers that adsorb onto rock surfaces (rather than gel aggregates that are filtered from solution).[18] As with weak gels, residual resistance factors provided by adsorbed polymers decrease with increasing permeability.[19,20] This behavior is opposite the desired trend.

A special property that has been reported for polymers and gels is an ability to reduce permeability to water by a greater factor than that to oil or gas (see Refs. 1-11 in Ref. 21). Under the right circumstances, this disproportionate permeability reduction could shut off water channels while causing minimum damage to oil or gas productivity.[5,7] Calculations indicate that this property is critical to the success of fluid-diversion treatments in production wells if zones will not be isolated during placement of the blocking agent.[5,7,21,22]

PARTICULATES

Placement. Several researchers proposed the use of particulates as blocking agents (see Refs. 104-111 in Ref. 2). With particulates, two different approaches can be taken to control placement. The first approach is commonly used in matrix acidizing.[23] If they are large enough relative to pore throats, particulates can form a filter cake on the rock surfaces. Since the largest volume of the injected suspension enters the most-permeable zone, the largest filter cake forms on that zone, and that filter cake can restrict flow to the greatest extent in the most-permeable zone. However, at best this method will equalize injection rates in the different zones.[23] If too much of the suspension is injected, flow will be restricted in all zones. Also, any beneficial flow diversion occurs at the wellbore. If flow is reversed (e.g., return of an oil well to production), the filter cake can be removed, and the effect of the diverting agent will be reversed. Finally, if this diversion method is combined with another blocking agent, such as a gelant, an undesirable placement results—the gelant is diverted <u>into</u> rather than away from the less-permeable zones.

The second placement approach using particulates relies on the relation between the particle size and the pore sizes of the zones of interest. In concept, a suspension of particles could penetrate readily into a high-permeability zone, while the particles are removed by filtration on the rock faces of less-permeable zones. If the fluid contains a gelant or other blocking agent, that blocking agent could be selectively placed in the high-permeability zone with minimum penetration into less-permeable zones.

For this second concept to work, several requirements must be fulfilled. First, the particles must be small enough to penetrate freely into the most-permeable zones. Second, the particles must be large enough to form an external filter cake on the rock surface of the less-permeable zones. Third, the particle size distribution must be sufficiently narrow. We developed a theoretical model to study the feasibility of using particulates to prevent gelant penetration into low-permeability zones during the placement process.[2] Our analysis indicated that to achieve selective placement using particulates with a normal size distribution, there is a maximum standard deviation of particle sizes that should not be exceeded for a given permeability contrast. For example, consider two zones with permeabilities of 10,000 md and 100 md, respectively. Assume a best case scenario where all particles less than 33.3 μm in diameter will flow freely through the 10,000-md rock and where all particles greater than 3.33 μm in diameter will form an external filter cake on the 100-md rock. Therefore, if monodisperse particles were available, a selective placement of a blocking agent could be achieved using any particles that were smaller than 33.3 μm and larger than 3.33 μm.

In reality, particles in a given suspension have a distribution of sizes. We have shown[2] that for a given standard deviation of a normal particle-size distribution, the maximum selectivity for placement of a blocking agent is achieved by choosing the average of the critical particle sizes of the high- and low-permeability zones as the mean particle size [in this example, (33.3+3.33)/2 = 18.3 μm]. If particles with a mean size of 18 μm are used in our example, the standard deviation of the size distribution must be smaller than 9 μm to achieve better selectivity than a water-like gelant without particulates.[2] To achieve the same selectivity as particulates with a monodisperse size of 18 μm, the standard deviation must be smaller than 4 μm. The maximum allowable standard deviation for selective placement decreases with decreasing permeability contrast.[2]

The above analysis is actually optimistic since it assumes that the rock has a single pore size. Because porous media contain a range of pore sizes, the particles used must have a narrower size distribution than was indicated above to achieve selectivity during placement.[2] The utility of particulates in controlling placement of blocking agents may also be limited by other factors that were not considered in our simple model. In particular, the ability of particles to penetrate into a given porous medium also depends on the influence of fluid velocity, particle concentration, and the surface chemistries of the particles and porous media.[24-26]

For our example case in Table 1, Rows 3 and 4 compare possible relative distances of penetration for particulates. If the particles are small enough to penetrate readily into both zones in our example and if the particles are suspended in a low-viscosity fluid, the relative distance of penetration could be 0.1 (Row 3 in Table 1)—the same value as that for low-viscosity gelants. For intermediate-sized particles (those small enough to flow readily into the high-permeability zone but large enough not to enter the low-permeability zone), the relative distance of penetration, in concept, could be zero (Row 4 in Table 1). On the surface, this behavior suggests a tremendous placement advantage over gelants. However, if the particles flow freely through the high-permeability rock, they may not provide a significant permeability reduction. Therefore, the particles by themselves are not expected to be an effective blocking agent in the high-permeability zones.

The above shortcoming could be remedied by incorporating a gelant or similar blocking agent with the suspended particles. This point is illustrated in Rows 5-7 in Table 1. Intermediate-sized particles suspended in a gelant (Row 6 in Table 1) could readily enter the high-permeability zone. However, the particles would form a filter-cake on the surface of the low-permeability zone—thus, minimizing gelant penetration. The 0.01 values in Row 6 of Table 1 are approximations that reflect that some gelant will inevitably enter the low-permeability zone during placement. Even so, the potential exists to achieve a substantially better placement than that possible with a gelant alone.

Rows 5 and 7 in Table 1 emphasize the importance of proper particle sizing when combining particulates with gelants. If particles are small enough to penetrate readily into both zones (Row 5 in Table 1), gelant placement will be no better than that for a low-viscosity gelant without particles. If the particles are too large to penetrate into either zone (Row 7 in Table 1) external filter cakes will form on both zones, and an excessive amount of gelant could enter the low-permeability zone (as expected from fluid diversion concepts in matrix acidizing[23]). In fact, the gelant could penetrate almost as far in the low-permeability zone as in the high-permeability zone (Row 7).

Permeability Reduction. The degree of permeability reduction caused by particulates can be separated into two components: (1) that associated with an external filter cake formed at the surface of a given zone and (2) that associated with an "internal filter cake" formed from particles trapped inside the porous medium. Since the external filter cake can be removed or circumvented by mechanical means (e.g., jet washing, backflow, or perforation), we are concerned primarily with the permeability reduction associated with the internal filter cake. For particles trapped inside a porous medium, the degree of permeability reduction qualitatively follows the same trend as that for weak gels. In particular, formation damage factors or residual resistance factors tend to increase with increasing ratio of particle size to pore size.[27-29] (This behavior has been reported when the ratio of particle size to pore size ranges from 1/14 to 1/3.[29]) This parallel in behavior between particulates and weak gels is not surprising since weak gels usually consist of a suspension of gel aggregates, which are a specific form of particulate. In concept, the potential improvements in placement that were discussed above with regard to particulates could also be achieved using suspensions of gel aggregates. Of course, the limitations also apply.

Hypothetically, particulates could reduce the flow capacity of water zones to a greater extent than oil zones. Small particles could be injected that are soluble in oil but not soluble in water.[30,31] These particles must be sized so that they enter the porous rock and become trapped by deep-bed filtration. Upon returning the well to production, the particles could significantly reduce the permeability of watered-out zones. In contrast, in zones with high fractional oil flows, the particles may quickly dissolve—thus restoring a high oil permeability.

PRECIPITATES (PHASE-TRANSITION PRODUCTS)

Placement. Several investigators proposed the use of precipitates (or other products of phase transitions) as blocking agents for fluid diversion in oil recovery processes (see Refs. 92-107 in Ref. 1). Typically, these processes involve forming a blocking agent in situ by mixing two incompatible chemical solutions in the formation. Alternatively, chromatographic separation in a formation can be exploited to form a blocking agent from a stable mixture. Llave and Dobson[32] described a recent example of the latter process. In their process, a low-viscosity surfactant-alcohol blend was injected. In the formation, the blend chromatographically separated, with the alcohol propagating more rapidly than the surfactant. After the alcohol was removed from the surfactant, the surfactant formulation became very viscous and restricted flow.

We surveyed the petroleum and patent literatures to investigate whether blocking agents formed in situ from phase transitions have potential advantages over gels.[1] In most cases, the flow properties of the proposed materials (before the phase transition) are no different from those of gelants. Therefore, their placement characteristics are similar to those of gelants. Specifically, for a given distance of penetration into a high-permeability zone, the distance of penetration into a less-permeable zone will be no less for a precipitate or phase-transition product than for a gelant with a water-like mobility. Certainly, the mechanism of forming the blocking agent can be different for a gel versus a phase-transition product. This difference could allow one blocking agent to penetrate deeper overall into a formation than another blocking agent. However, it will not change the relative placement properties (i.e., the distance of penetration in one zone relative to that in a nearby zone during unrestricted injection).[4] Thus, in our example in Table 1, placement of these materials is not better than that achieved using a low-viscosity gelant (Row 8 in Table 1).

Permeability Reduction. Very little work has been reported on the permeability dependence of the permeability-reduction properties of precipitates. We suspect that they usually will be the same as those for particulates. As mentioned earlier, residual resistance factors tend to increase with increasing ratio of particle size to pore size.[27-29] (Particulates that enter porous rock reduce the flow capacity of low-permeability rock by a greater factor than in high-permeability rock.)

Thompson and Fogler[31] investigated the use of "reactive water-blocking agents" to plug water zones in preference to oil zones in production wells. These chemicals are dissolved in oil and then injected. They react upon contact with water to form a precipitate or solid barrier. Ideally, watered-out zones will be restricted by blocking agents formed at the front between the displaced water bank and the injected bank of reactive chemicals, while no blocking agent should form in zones with high oil saturations. To maximize formation of blocking agents in water zones, Thompson and Fogler proposed using a relatively viscous oil as a carrier fluid for the reactive chemicals. When the well is returned to production after injecting the reactive chemicals, water should finger through the bank of reactive chemicals—thereby promoting mixing and formation of the blocking agent. One of the main challenges in using these materials is that reaction with residual water in the oil-bearing zones could damage oil productivity. More work is needed to assess the potential of reactive water-blocking agents, especially their effects on oil productivity.

MICROORGANISMS

Many people have proposed the use of microorganisms as blocking agents (see Refs. 1-24 in Ref. 3). In most of these proposals, placement of the microorganisms is dictated by placement of the nutrients. Since the flow properties of the nutrients are no different from those of gelants, their placement characteristics are similar to those of gelants. Specifically, for a given distance of penetration into a high-permeability zone, the distance of penetration into a less-permeable zone will be no less for the nutrient (and the microorganism) than for a gelant with a water-like mobility. If a viscous nutrient is used (e.g., molasses or corn syrup), microorganism penetration into less-permeable zones increases.[4,11]

From one perspective, microorganisms could be viewed as particulates. Because of their narrow size distribution, certain microorganisms could, in concept, provide the advantageous placement characteristics associated with monodisperse particles (discussed earlier). A suspension of microorganisms could penetrate readily into a high-permeability zone, while size restrictions prevent them from entering less-permeable zones. Bae *et al.*[33] proposed the use of spores to act by this mechanism. They observed spores that propagate through Berea sandstone with permeabilities greater than 710 md but that do not propagate through cores with permeabilities less than 380 md. Once placed, nutrients could be provided so that the microorganisms could restrict flow (i.e., by growing or generating biomass or polymers). Thus, for our example in Table 1, microorganisms conceptually could provide a placement similar to that for intermediate-sized particles suspended in a gelant (Row 6 in Table 1).

Two important restrictions must be noted when using microorganisms in this mode. First, growth, aggregation of microorganisms, and adsorption onto pore walls must be limited during placement. Otherwise, these phenomena could greatly limit the distance of microorganism penetration into the high-permeability zones. Second, the microorganisms should be near-spherical in shape during placement. Elongated microorganisms act as particulates with a significant size distribution.[3] As mentioned earlier, the placement advantage for particulates will be lost unless the size distribution is very narrow.

FOAMS

Placement. A considerable volume of theoretical, laboratory, and field work has been performed to evaluate the use of foams as mobility-control agents during steam and high-pressure gas floods (see Refs. 2-69 in Ref. 2). Much less work has been done to evaluate the use of foams as blocking agents. The distinction between a blocking agent and a mobility-control agent is an important concept to understand. A mobility-control agent should penetrate as much as possible into the less-permeable zones so that oil can be displaced from poorly swept zones. In contrast, we wish to minimize penetration of blocking agents into the less-permeable, oil-productive zones. Any blocking agent that enters the less-permeable zones can hinder subsequent injected fluids (e.g., water, CO_2, steam) from entering and displacing oil from those zones.

Many field results demonstrate that foams usually act more effectively as mobility-control agents than as blocking agents. For example, in cases where vertical injection profiles were measured before, during, and after foam injection, the profiles were consistently improved during foam injection—demonstrating the ability of the low-mobility foams to shift flow from high-permeability zones into less-permeable zones.[34-38] Also, when gas or water injection was resumed after foam injection, the profiles quickly reverted to profiles that were the same or worse than those observed before foam injection.[34-39] This behavior is consistent with expectations for injection of a high-mobility fluid following a bank of low-mobility fluid in a heterogeneous system.[11] This behavior is opposite to that desired for a blocking agent.

Nevertheless, in concept, several phenomena could allow foams to be superior to gels as blocking agents, in some circumstances. At present, these circumstances are hypothetical; very few conditions have been verified experimentally or in field applications. Details of our analyses of these circumstances are presented in Ref. 2. In what follows, we summarize the findings of these analyses.

Two phenomena, the limiting capillary pressure[40-42] and the minimum pressure gradient for foam generation,[34] could allow low-mobility foams to form in high-permeability zones but not in low-permeability zones. Exploiting these phenomena during foam placement requires that (1) under given reservoir conditions, a gas/liquid composition must be identified that will foam in high-permeability zones but not in low-permeability zones, (2) the foam must not easily collapse or wash out from the high-permeability zones, and (3) the aqueous phase must <u>not</u> contain a gelant or other reactive blocking agent.

For our example in Table 1, an ideal placement could be realized if foam forms in the high-permeability zone but does not form in the low-permeability zone (Row 9 in Table 1). In contrast, an extremely unfavorable placement results if foam forms in both zones. As shown in Row 10 of Table 1, the foam can penetrate almost as far in the low-permeability zone as in the high-permeability zone. This behavior is expected for viscous fluids when free crossflow can occur.[11,12] However, if crossflow cannot occur, the relative distance of penetration into the low-permeability zone is significantly greater than expected for simple viscous fluids[2] (compare Rows 2 and 10 in Table 1). If gelant is included with the foam (Row 11 in Table 1), a very undesirable placement results regardless of whether foam forms in the less-permeable zone.[2]

In cyclic steam projects, foam placement could be aided by gravity effects combined with very large mobility contrasts between the foam and the displaced oil. For cyclic steam injection projects where the foam was intended to act as a blocking agent, a common observation for successful field applications was that steam and oil flow after the foam treatment was diverted away from upper zones in favor of the middle or lower zones.[43] These results suggest that gravity effects aided foam placement in the upper zones.

A circumstance where the presence of a preformed gel could aid placement of a foam can be inferred from the work of Craighead *et al.*[44] During hydraulic fracturing, foamed gels show significantly lower leakoff rates than foams or foamed polymers.[44] Logically, preformed foamed gels may propagate substantial distances along fractures with minimum leakoff. This argument parallels that given for injecting preformed gels into fractured systems.[6] However, a potential advantage over ordinary gels is that the foamed gels may be more likely to extrude through fractures without developing excessive pressure gradients. This concept needs to be tested experimentally.

Permeability Reduction. Problems with foam propagation and stability present challenges for foam applications both as mobility-control agents and as blocking agents.[2] In many cases, foam stability is significantly reduced by the presence of oil.[45,46] Hypothetically, this phenomenon could be exploited to optimize the use of a foam blocking agent in oil production wells. When oil wells are returned to production after foam injection, foams could collapse more rapidly in oil zones than in water zones. This behavior is most likely to be exploitable if the water zones contain no residual oil. Foam washout from the water zones could be reduced by incorporating a polymer or gel into the foam. If a gelant is used, the foam must be produced from the oil zones before gelation occurs; otherwise, the oil zones could be damaged.

Another potential advantage of foamed gels is that they may allow more control in achieving low or intermediate residual resistance factors.[47] To explain, strong gels (without foam) can provide predictable and reproducible residual resistance factors because gelation in the porous medium is fairly complete.[15] Because these gels fill most of the aqueous pore space,[15] residual resistance factors are usually very high (10^3-10^6). However, we sometimes desire lower residual resistance factors (e.g., 1-100), that are associated with weak gels. Unfortunately, for the reasons mentioned earlier, weak gels provide low to intermediate residual resistance factors that are often unpredictable.[15] If a foamed gel is used that incorporates a strong gel in the aqueous phase, the thin gel films that separate the gas bubbles should be formed reproducibly, and they may allow intermediate residual resistance factors to be attained more reliably. This concept also needs to be tested experimentally.

For foams, gas residual resistance factors can increase with increasing permeability.[45] This behavior could be exploited when using foam as a gas blocking agent. A similar phenomenon has not been observed for water residual resistance factors in the presence of foam.[45] Gels and foams are known to show different permeability reductions for different phases.[21,45,46] Experimental work is needed to establish the permeability reduction properties of foamed polymers and foamed gels.[48]

EMULSIONS

Can emulsions be made to work better than gels as blocking agents? Analysis of the literature (Refs. 70-103 in Ref. 2) suggests no reason to believe that emulsions have any placement or permeability-reduction advantages over gelants and gels.[2] For concentrated emulsions (either oil-in-water or water-in-oil), their behavior in porous media can be described using standard relative-permeability concepts.[49,50] Therefore, the placement properties of concentrated emulsions are similar to those of viscous gelants.[5] Also, the literature indicates that concentrated emulsions provide very low permeability-reduction values (residual resistance factors less than 1.5).[2,49,50] Furthermore, residual resistance factors provided by concentrated emulsions do not increase with increasing initial rock permeability.[49,50]

Dilute emulsions show behavior that can be described by a modified deep-bed filtration theory.[51-53] Ref. 2 contains a detailed examination of the literature and models that describe the flow of dilute emulsions through porous media. We can summarize the results of this analysis as follows: although several features of emulsion flow through porous media remain unanswered, our analysis of the literature indicates that emulsions or emulsion/gel combinations will not perform significantly better than gels as blocking agents, particularly in the areas of placement characteristics and permeability-reduction properties.

For our example problem, results shown in Row 12 of Table 1 were obtained based on flow properties for dilute emulsions that were reported in the literature.[2,51,52] Our calculations indicate that at best, the placement properties of emulsions will approach those for a low-viscosity gelant.

CONCLUSIONS

In this paper, we focused on ideas that may allow the development of blocking agents with placement and/or permeability-reduction properties that are superior to those of gels. We identified foams, particulates with gelant, and microorganisms as materials that conceptually could provide superior placement properties. However, in each case, important requirments must be fulfilled before the materials will provide superior performance.

For particulates, the particles must (1) be small enough to penetrate readily into the high-permeability zone, (2) be large enough to form an effective external filter cake on the low-permeability zones, (3) have a sufficiently narrow size distribution, (4) not aggregate or adsorb excessively on pore walls during placement, and (5) be suspended in a gelant (preferably, a low viscosity gelant) or similar reactive blocking agent.

For microorganisms, the first four restrictions for particulates (above) also apply.

For foams, (1) under the given reservoir conditions, a gas/liquid composition must be identified that will foam in high-permeability zones but not in low-permeability zones, (2) the foam must not easily collapse or wash out from the high-permeability zones, and (3) the aqueous phase must not contain a gelant or other reactive blocking agent Several other special circumstances were discussed where foams could be useful as blocking agents.

With each of the above materials, additional work is needed to identify specific compositions that will provide the desired improvements.

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