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Wall-Effect/Gel-Droplet Model of Disproportionate Permeability Reduction
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Abstract
Many polymers and gels can reduce the permeability to water more than that to oil or gas. However, the mechanism of this disproportionate permeability reduction is not clear. This paper considers a promising potential explanation that is based on a combined "wall-effect" and "gel-droplet" model. Disproportionate permeability reduction can be explained by a wall-effect model if the gelant is prepared from or matches the wetting phase, and by a gel-droplet model if the gelant is prepared from or matches the non-wetting phase. The combined model predicts that disproportionate permeability reduction should increase with increasing residual non-wetting-phase saturation. New experimental results support this prediction. Maintaining high residual oil saturations in the treated region of an oil zone could significantly reduce damage to oil productivity after a gel treatment.

The disproportionate permeability reduction increased with increased pressure drawdown between 45 psi/ft to 180 psi/ft. Therefore, to a certain extent, an increase in pressure drawdown after a gel treatment might reduce damage to oil productivity without increasing water production.

Introduction
The objective of polymer and gel treatments in production wells is to reduce water production without damaging oil productivity. Many polymers and gels can reduce the permeability to water more than that to oil or gas.[1] This property is critical to the success of water-shutoff treatments in production wells if hydrocarbon-productive zones cannot be protected during placement.[2,3] However, the magnitude of the effect has been unpredictable from one application to the next. Presumably, the effect would be more predictable and controllable if we understood why the phenomenon occurs. In this study, we first briefly review the validity of several possible explanations for this disproportionate permeability reduction. Then, we investigate a promising mechanism—a combined wall-effect and gel-droplet model. To test this potential mechanism, we examined the effects of residual oil saturation, pressure drawdown, absolute permeability, and core wettability.

Review of Previous Mechanisms
Our previous studies showed that the disproportionate permeability reduction was not caused by simple hysteresis of relative permeabilities or by gel breakdown during successive injection of oil and water banks.[1,2] This phenomenon was observed in core experiments using constant-pressure and constant-rate drive. Also, the disproportionate permeability reduction did not vary with core length.[4] Finally, this phenomenon was observed not only with polymers or weak polymer-based gels, but also with a resorcinol-formaldehyde gel and strong polymer-based gels.[1] Thus, the effect does not appear to be an experimental artifact.

Several theories for the disproportionate permeability reduction were tested previously.[1,4-7] Gravity and lubrication effects were discounted as significant mechanisms.[6] Also, gel shrinking and swelling were unlikely to be responsible for this phenomenon. A mechanism involving a balance between capillary forces and gel elasticity was also considered.[5,8] Our experimental results suggested that this mechanism was valid only in micromodels and small glass tubes, not in porous rock.[5] Experiments revealed that wettability may play a role in the disproprotionate permeability reduction.[7,9,10] However, wettability effects, by themselves, are insufficient to explain the underlying cause of the phenomenon.[5,7] Another promising mechanism relies on oil and water following segregated pathways on a microscopic scale. Although this segregated pathway theory has merit,[5] several experimental results appear inconsistent with the proposed mechanism.[4,7,11] (This mechanism will be discussed in greater detail in a future paper.)

Wall-Effect Model
Zaitoun *et al.*[9] attributed the disproportionate permeability reduction to wall effects resulting from an adsorbed polymer layer on the pore walls. Fig. 1 shows that in a strongly water-wet rock, residual oil droplets at the center of the pores can

significantly reduce the effective width of the water channels during waterflooding. In contrast, this restriction may not exist during oilflooding. Therefore, for a given thickness of an adsorbed polymer layer, the permeability reduction for water during waterflooding is greater than that for oil during oilflooding. Following similar logic, if the adsorbed layer on the pore walls is either a polymer or a water-based gel, the wall-effect model could explain why some water-based gels exhibit disproportionate permeability reduction in strongly water-wet cores (Fig. 1).

Row 1 of Table 1 lists an example illustrating this behavior for a water-based gel (0.5% Alcoflood 935 HPAM, 0.0313% Cr(III)-acetate, 0.0121% $CrCl_3$, 1% NaCl, and 0.01% $CaCl_2$) in a strongly water-wet rock (700-md Berea sandstone with a residual oil saturation of Soltrol 130, 41°C). The gel reduced the permeability to water by a factor of 10,100 (i.e., the water residual resistance factor, F_{rrw}, was 10,100), while the permeability to oil was reduced by a factor of 59 (i.e., the oil residual resistance factor, F_{rro}, was 59). (Details of the experimental procedures and results for this and other corefloods that are summarized in Tables 1-5 can be found in Refs. 4, 7, and 11. All results were obtained at 41°C.)

In an oil-wet system, Zaitoun et al.[9] proposed that polymer could cover most of the rock surface by anchoring on the small part of the rock surface that remains water-wet. The layer of polymer covering the oil-wet surface would shift the wettability toward water-wet. In this way, the polymer could reduce the permeability to water more than that to oil in an oil-wet core. Zaitoun et al.[9] reported that the capillary pressure of a silane-treated oil-wet sandstone core shifted from negative before a gel treatment to positive after treatment. Also, the polymer reduced the permeability to water more than that to oil in the oil-wet core. Based on these findings, they concluded that the adsorbed polymer layer was responsible for the disproportionate permeability reduction in both the oil- and water-wet cores.

If this theory is correct, the disproportionate permeability reduction should vanish in strongly oil-wet polyethylene cores where there is no water-wet surface on which polymer or gelant molecules can anchor. However, we found that a water-based gel [Cr(III)-acetate-HPAM described above] reduced the permeability to water much more than that to oil in an oil-wet polyethylene core (Row 2 in Table 1). In particular, F_{rrw} was 90,000, while F_{rro} was 375. (Ref. 7 provides experimental details.) This finding does not support the wall-effect theory.

Fig. 2 illustrates that the wall-effect model can explain why an oil-based gel reduced the permeability to oil more than that to water in a strongly oil-wet core. An oil-based gel could form a gel layer on the pore walls of a strongly oil-wet porous medium. In this case, the presence of residual water droplets at the center of the pores could significantly reduce the effective width of the oil channels during oilflooding. However, this restriction may not exist during waterflooding. Therefore, for a given thickness of an adsorbed layer of the oil-based gel, the permeability reduction for oil during oilflooding is greater than that for water during waterflooding. Row 4 in Table 1 illustrates this behavior for an oil-based gel (18% 12-

hydroxystearic acid in Soltrol 130) in a strongly oil-wet polyethylene core. In this experiment (detailed in Ref. 7), the oil-based gel was prepared from the same oil that formed the wetting phase (Soltrol 130). In this example, F_{rrw} was 85, while F_{rro} was 375.

The wall-effect model cannot explain why our oil-based gel reduced the permeability to oil more than that to water in a strongly water-wet Berea sandstone. (Our oil-based gel probably will not adsorb onto strongly water-wet pore walls.) In this example (Row 3 of Table 1), F_{rro} was 300, while F_{rrw} was 34. These findings suggest that the wall-effect model can explain the disproportionate permeability reduction only when the gelant is prepared from or matches the wetting phase.

Gel-Droplet Model

The observations that could not be explained by the wall-effect model can be explained using a gel-droplet model (inspired by Nilsson et al.[10]). In this model, a gel droplet forms at the center of a pore, causing more restriction to flow of the wetting phase than to flow of the non-wetting phase.

Consider the case where a water-based gelant is used to treat an oil-wet core (e.g., Row 2 of Table 1). Before gel placement, when water flows through an oil-wet pore (top of Fig. 3), the only restriction to water flow is a thin film of oil on the pore walls. In contrast, when oil flows through the same pore, a residual water droplet in the pore restricts oil flow. (This partially explains why the endpoint permeability of the wetting phase is lower than that of the non-wetting phase.)

During gel placement, the water-based gelant flows through the center of the oil-wet core. (The gelant is the non-wetting phase.) After gelation, a gel droplet forms at the center of the pore, replacing the residual water droplet. If the size of the gel droplet is the same as that of the residual water droplet (Fig. 3), the volume fraction of the pore available to oil flow remains the same as before treatment. However, the presence of the gel droplet significantly reduces the volume fraction of the pore available to water flow. (Recall that the only restriction to water flow before treatment was the thin film of oil on the pore wall.) Thus, the gel can reduce permeability to water without affecting permeability to oil. Of course, if the gel droplet is larger than the residual water droplet, the permeability to oil will be reduced. Also, the disproportionate permeability reduction should diminish when the size of the gel droplet falls below that of the residual water droplet.

Following similar logic, Fig. 4 illustrates that an oil-based gel should reduce the permeability to oil more than that to water in a strongly water-wet rock. In support of this theory, Row 3 of Table 1 shows that an oil-based gel reduced the permeability to oil more than that to water in a strongly water-wet system.[7] In particular, F_{rro} was 300, while F_{rrw} was 34.

In a strongly water-wet rock, the model predicts that a strong water-based gel could block the pores completely by encapsulating the residual oil droplets. (The water-based gel is the wetting phase.) Even with syneresis, the gel droplet could occupy a significant volume fraction of the pore, thereby significantly reducing permeability to both water and oil. However, a strong water-based gel reduced the permeability to

water much more than that to oil in a strongly water-wet rock (Row 1 of Table 1). This finding does not support the gel-droplet model. Also, according to this model, an oil-based gel should block strongly oil-wet pores completely by encapsulating the residual water droplets, thereby significantly reducing permeability to both water and oil. Yet, an oil-based gel reduced the permeability to oil more than that to water in an oil-wet system (Row 4 of Table 1). These findings suggest that the gel-droplet model can explain the disproportionate permeability reduction only when the gelant is prepared from or matches the non-wetting phase.

Combined Model

In review, the disproportionate permeability reduction can be explained using the wall-effect model if the gelant is prepared from or matches the wetting phase. In contrast, when the gelant is prepared from or matches the non-wetting phase, the gel-droplet model explains the disproportionate permeability reduction. In a combined model, we simply assume that the individual models apply for the appropriate circumstances. In particular, the wall-effect model applies for water-based gels in water-wet cores or for oil-based gels in oil-wet cores. The droplet model applies for water-based gels in oil-wet cores or for oil-based gels in water-wet cores.

In this work, we use the ratios, F_{rrw}/F_{rro}, or F_{rro}/F_{rrw}, to quantify disproportionate permeability reduction. Higher ratios indicate more pronounced disproportionate permeability reduction.

Effect of Residual Oil Saturation. According to the combined wall-effect/gel-droplet model, residual non-wetting-phase droplets play an important role in the disproportionate permeability reduction. Usually, the residual non-wetting-phase droplets are trapped in the larger pores in globules in a porous medium.[12] The combined model predicts that the disproportionate permeability reduction should increase when the total number of pores occupied by the residual non-wetting-phase droplet increases. In other words, the disproportionate permeability reduction should increase with increasing residual non-wetting-phase saturation.

One way to test this theory is to perform oil/water experiments in cores of different residual non-wetting-phase saturation. Under a specific range of conditions, lowering the capillary number increases the residual non-wetting-phase saturation.[12] Therefore, we performed oil/water experiments in strongly water-wet Berea cores using our standard Cr(III)-acetate-HPAM gel. We varied the residual oil saturation by using different capillary numbers during waterflooding before the gel treatment. During gelant injection, we stayed below the capillary number used during waterflooding before the gel treatment to avoid mobilizing the residual oil in the core. After gel placement and formation in the core, residual resistance factors were measured below the capillary number as well. For each capillary number, two similar oil-water experiments were performed: one with oil injected first after gel placement to measure oil residual resistance factor, F_{rro}, and the other with brine injected first after gel placement to measure water

residual resistance factor, F_{rrw}. Table 2 shows that lowering the capillary number from 10^{-4} to 10^{-5} increased the residual oil saturation from 0.21 to 0.35. The increase in residual oil saturation resulted in a 4.5-X increase in the disproportionate permeability reduction. (F_{rrw}/F_{rro} increased from 50 to 223.) This finding supports the combined wall-effect and gel-droplet model.

In field applications, water zones are often completely watered out with low residual oil saturations while the oil zones contain higher residual oil saturations. This situation may be helpful in maximizing the disproportionate permeability reduction. As illustrated in Table 3, for our standard Cr(III)-acetate-HPAM gel, increasing the residual oil saturation in the oil zone from 0.21 to 0.35 without changing that in the water zone could result in a 22-X increase in the disproportionate permeability reduction. (F_{rrw}/F_{rro} increased from 50 to 1,100.) Table 3 also shows that the increase in the disproportionate permeability reduction resulted from a significant decrease in F_{rro}. These findings suggest that maintaining a high residual oil saturation in the gel-treated region of an oil zone could significantly reduce damage to oil productivity.

Effect of Rock Permeability. With the combined wall-effect/gel-droplet model, as well as other models, one might expect the disproportionate permeability reduction to vary with rock permeability or pore size. Therefore, we performed several experiments to examine the effect of rock permeability. These studies have an important practical value since bypassed oil is commonly found in less-permeable zones, while the high-permeability channels are watered out. Ideally, the disproportionate permeability reduction would be more pronounced in low-permeability zones than in high-permeability.

Table 4 summarizes the effects of rock permeability from several tests. As before, the water-wet cores were Berea sandstone, the oil-wet cores were polyethylene, the water-based gel was Cr(III)-acetate-HPAM, and the oil-based gel was 18% 12-hydroxystearic acid in Soltrol 130. Details from these experiments can found in Refs. 4, 7, and 11.

For the water-based gel in water-wet cores, F_{rrw}/F_{rro} decreased from 65 to 6 as the absolute core permeability decreased from 1.3 to 0.16 darcys (Table 4). The F_{rrw} values were about the same for the two cores, but F_{rro} was 11 times greater for the 0.16-darcy core than the 1.3-darcy core. Invoking the wall-effect model (Fig. 1), this result suggests that during oil flow, the ratio of adsorbed gel thickness to pore throat radius was much more important (i.e., restrictive to oil flow) in the 0.16-darcy rock than in the 1.3-darcy rock.

For the oil-based gel in water-wet cores, F_{rro}/F_{rrw} increased from 5 to 14 as the absolute core permeability decreased from 1.8 to 0.17 darcys (Table 4). This change was much more moderate than that in the previous case. Both F_{rro} and F_{rrw} were affected by permeability, although F_{rrw} experienced the greatest change. Invoking the droplet model (Fig. 2), an explanation for this behavior is not obvious by considering a single pore. However, if one considers that a distribution of

pore sizes exists, an explanation becomes more evident. The smaller pores should be filled with the wetting-phase but no gel droplets. The larger pores contain both the wetting phase and the gel droplets. Both the small and the large pores will contribute to the total flow of the wetting phase. However, gel droplets only affect flow through the larger pores. As the absolute permeability decreases, the ratio of small pores to large pores increases. Thus, the wetting-phase flow contribution from the smaller pores becomes proportionately more important as permeability decreases, and the residual resistance factor to the wetting phase decreases correspondingly. This argument does not explain the decrease in F_{rro} with decreasing permeability, however. More work will be needed to understand that behavior.

For the water-based gel in oil-wet cores, F_{rrw}/F_{rro} decreased from 240 to 130 as the absolute core permeability decreased from 15 to 7 darcys (Table 4). As in the previous case, this change was moderate relative to the case for a water-based gel in an water-wet core. Both F_{rro} and F_{rrw} were affected by permeability. The arguments from the previous paragraph can be used to explain why F_{rro} decreased from 375 in the 15-darcy core to 192 in the 7-darcy core. However, the associated decrease in F_{rrw} values awaits an explanation.

Effect of Pressure Drawdown. We wondered whether pressure drawdown could be exploited to maximize the disproportionate permeability reduction. To address this issue, we performed core floods where different pressure gradients were applied during oil or water injection after gel formation. Details of these experiments can be found in Ref. 7.

For each pressure gradient, two similar oil-water experiments were performed using a different core for each experiment: one with oil injected first after gel placement to measure oil residual resistance factor, F_{rro}, and the other with brine injected first after gel placement to measure water residual resistance factor, F_{rrw}. In total, eight oil/water experiments were performed using eight different Berea cores of similar permeability. The gel contained 0.5% HPAM, 0.0313% Cr(III)-acetate, 0.0121% $CrCl_3$, 1% NaCl, and 0.1% $CaCl_2$. Soltrol 130 was the oil phase.

Table 5 shows that F_{rrw}/F_{rro} increased with increased pressure gradient between 45 psi/ft to 180 psi/ft. The increase in pressure gradient caused a 50% reduction in F_{rro} while F_{rrw} remained relatively unchanged. F_{rrw}/F_{rro} increased from 233 at 45 psi/ft to 410 at 180 psi/ft. Therefore, to a certain extent, an increase in pressure drawdown after treatment might reduce productivity damage to oil without affecting the ability of the gel to reduce water production. However, at 225 psi/ft, a dramatic decrease in F_{rrw} occurred and the disproportionate permeability reduction disappeared (F_{rrw}/F_{rro}~1). This result implies gel washout (by brine) from the rock at 225 psi/ft.

Future Work
We do not suggest that the mechanism for the disproportionate permeability reduction has been clearly established. Unresolved questions remain regarding the proposed wall-effect/gel-droplet model. Also, at least one other mechanism,

the segregated pathway theory, has sufficient merit to warrant further study, even though problems are apparent with this mechanism as well.[4-7,11] Therefore, considerable additional work is needed to elucidate the mechanism of disproportionate permeability reduction.

Conclusions
1. If a gelant is prepared from or matches the wetting phase, a wall-effect model can explain the disproportionate permeability reduction. In contrast, when the gelant is prepared from or matches the non-wetting phase, a gel-droplet model can explain the phenomenon.
2. In strongly water-wet Berea cores, the disproportionate permeability reduction increased with increased residual oil saturation. This finding is consistent with predictions from a combined wall-effect/gel-droplet model. However, additional work is required to verify the model.
3. Maintaining high residual oil saturations in the gel-treated region of an oil zone could significantly reduce damage to oil productivity.
4. In Berea sandstone, the disproportionate permeability reduction increased with increased pressure drawdown between 45 psi/ft to 180 psi/ft. Therefore, to a certain extent, an increase in pressure drawdown after a gel treatment might reduce damage to oil productivity without increasing water production.
5. The wall-effect/gel-droplet model can partially account for the permeability dependence of residual resistance factors. However, some aspects of the permeability dependence remain to be explained.

Nomenclature
F_{rro} = oil residual resistance factor (oil mobility before gel divided by oil mobility after gel)
F_{rrw} = water residual resistance factor (water mobility before gel divided by that after gel)
k_w = relative permeability to water, darcys [μm^2]
N_{ca} = capillary number based on darcy velocity
S_{or} = residual oil saturation

Acknowledgements

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SI Metric Conversion Factors

cp x 1.0*   E-03   = Pa·s
ft x 3.048*   E-01   = m
in. x 2.54*   E+00   = cm
mD x 9.869 233   E-04   = μm^2
psi x 6.894 757   E+00   = kPa

*Conversion is exact.

Table 1—Effect of Rock Wettability and Gel Type on Disproportionate Permeability Reduction

Core Type	Gel Type	F_{rrw}	F_{rro}	F_{rrw}/F_{rro} or F_{rro}/F_{rrw}
water-wet[1]	water-based[3]	10,100	59	171
oil-wet[2]	water-based[3]	90,000	375	240
water-wet[1]	oil-based[4]	34	300	9
oil-wet[2]	oil-based[4]	85	375	4.4

[1] 700-mD Berea sandstone, [2] 15-darcy polyethylene artificial core
[3] Cr(III)-acetate-HPAM, [4] 12-hydroxystearic acid and Soltrol-130

Table 2—Effect of Residual Oil Saturation

Gel: 0.5% HPAM, 0.0313% Cr(III)-acetate,
0.0121% $CrCl_3$, 1% NaCl, 0.1% $CaCl_2$
Cores: 1.5 darcy Berea sandstone

S_{or}	N_{ca}	F_{rrw}	F_{rro}	F_{rrw}/F_{rro}
0.21	10^{-4}	26,400	525	50
0.35	10^{-5}	5,360	24	223

Table 3—Effect of Residual Oil Saturation

Gel: 0.5% HPAM, 0.0313% Cr(III)-acetate,
0.0121% $CrCl_3$, 1% NaCl, 0.1% $CaCl_2$
Cores: 1.5 darcy Berea sandstone

S_{or} (Water zone)	S_{or} (Oil zone)	F_{rrw}	F_{rro}	F_{rrw}/F_{rro}
0.21	0.21	26,400	525	50
0.21	0.35	26,400	24	1,100

Table 4—Effect of Rock Permeability

| Condition	k_w, darcys	F_{rrw}	F_{rro}	F_{rrw}/F_{rro} or F_{rro}/F_{rrw}
Water-based gel, Water-wet cores	1.3	2,750	42	65
	0.16	2,850	470	6
Oil-based gel, Water-wet cores	1.8	184	860	5
	0.6	34	300	9
	0.17	25	350	14
Water-based gel, Oil-wet cores	15	90,000	375	240
	7	25,000	192	130

Table 5—Effect of Pressure Drawdown

Gel: 0.5% HPAM, 0.0313% Cr(III)-acetate,
0.0121% $CrCl_3$, 1% NaCl, 0.1% $CaCl_2$
Cores: 1.5-darcy Berea sandstone

Pressure Gradient, psi/ft	F_{rrw}	F_{rro}	F_{rrw}/F_{rro}
45	47,000	202	233
90	30,000	127	236
180	42,200	103	410
225	73	107	~1

$F_{rrw} > F_{rro}$
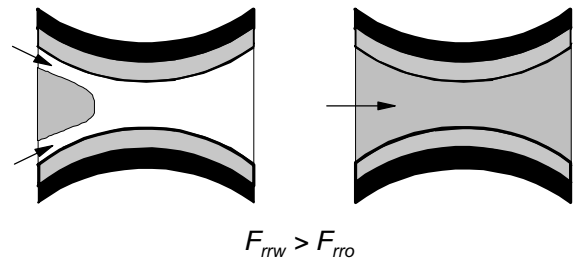
☐ Oil   ☐ Water   ■ Rock   ☐ Polymer or Water-Based Gel

Fig. 1—Wall-effect model proposed by Zaitoun *et al.*[9]

$F_{rro} > F_{rrw}$
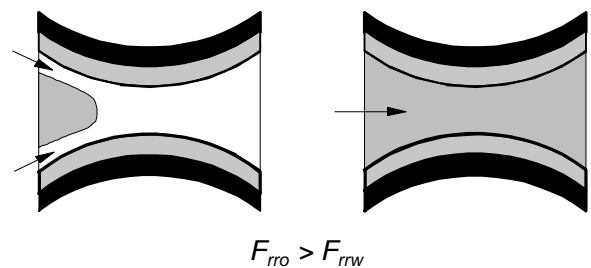
☐ Water   ☐ Oil   ■ Rock   ☐ Oil-Based Gel

Fig. 2—Wall-effect model proposed by Zaitoun *et al.*[9]

Before Treatment

After Treatment

$$F_{rrw} > F_{rro}$$

☐ Oil   ☐ Water   ■ Oil-Wet Rock   ☐ Water-based gel

Fig. 3—Gel-droplet model inspired by Nilsson *et al.*[10]

Before Treatment

After Treatment
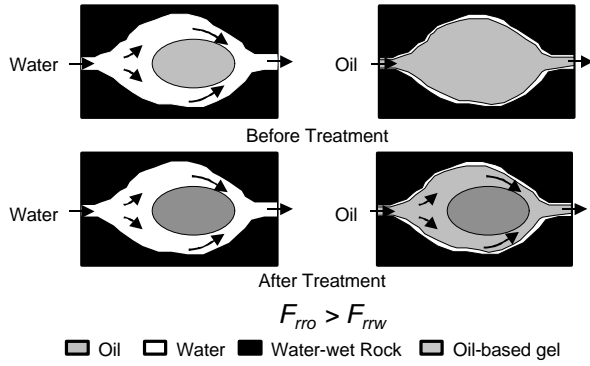
$$F_{rro} > F_{rrw}$$

☐ Oil   ☐ Water   ■ Water-wet Rock   ☐ Oil-based gel

Fig. 4—Gel-droplet model inspired by Nilsson *et al.*[10]