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Capillary Continuity in Fractured Oil Reservoirs

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Abstract

In well fractured carbonate reservoirs the gas/oil gravity drainage from the gas-invaded zone is the dominating oil producing process. When the gravitational forces exceed the capillary forces, the matrix blocks, which are surrounded by gas, will release their oil.

The results of our experimental works reveal that, depending on the interfacial tension, spreading coefficient, rock wettability, and surface roughness, there is a critical fracture aperture size, t_{fc}. *Rock wettability, surface roughness and spreading coefficient play their rules in formation of oil droplets, while the maximum size of the droplet is controlled by the amount of surface tension. When the fracture aperture is more than* t_{fc}, *the continuity is via solid compressed spacers and/or oil film around them, which at actual reservoir conditions may be considered as non-effective capillary continuity. Whereas for the case that the fracture aperture is less than its critical value, the capillary continuity is mainly through liquid bridges, which due to their high transmissibility will result in an effective capillary continuity between blocks.*

Two new definitions for horizontal fracture capillary pressure based on the type of capillary continuity have been presented. The Laplace formula and pressure difference between the fracture gas and the matrix oil may be used for the calculation of fracture capillary pressure for non-effective and effective continuity, respectively.

Keywords: Fractured reservoir, Capillary continuity, Block to block effect, Gravity drainage, Dual porosity, Gas invaded zone

Introduction

A fractured porous medium is comprised of two different systems. The first is matrix porous media with high porosity and low permeability. The second is the fracture network with high permeability and low porosity. In a fractured reservoir, as production begins and reservoir pressure drops, the gas oil contact in the fracture descends below that in the matrix, and some of the oil bearing, matrix blocks become surrounded by gas. Those matrix blocks in the gas-invaded zone (surrounded by gas) will undergo a gravity drainage process when the gravitational forces exceed the capillary forces. The density difference between the gas in the fracture and the oil in the matrix is the main driving force, which is counteracted by the matrix capillary pressure.

For a single-block, initially the oil will leave a block at its maximum flow rate and the rate will gradually decrease toward zero (as the equilibrium between capillary and gravity forces approaches).

Although many researchers have studied the process of gravity drainage in fractured

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porous media, no final conclusions have been reached on the physics of this process so far. The role of the horizontal fracture in the gravity drainage process from a stacked block have imposed a real challenge to researchers during the last twenty years.

Literature Review. The first attempt to specify the conditions for having stable liquid bridges across fractures was done by Saidi [1]. He concludes that if the fracture aper-ure is about 50 μm or more, capillary continuity between a stack of blocks cannot be realised. Based on the results of their simulation of fractured reservoirs Gilman and Kazemi [2], mentioned that horizontal frac-tures would reduce recovery and cause capil-lary discontinuity between matrix blocks. Stones et al. [3] argued that since the permeability of the fracture has been shown to be much greater than that of the matrix, flow across the fracture probably does not limit the eventual recovery. They also illustrated that at some experimental conditions bridging does not appear to be a major factor in eventual recovery. They concluded that since observed liquid recoveries from fractured porous media are lower than for comparable fully consolidated sand, fractures must change some fundamental aspect of flow. They suggested that no general agree-ment has been reached on the actual physical processes involved and little experimental work has been presented.

Firoozabadi [4] emphasized that the Young-Laplace equation could be the framework for fracture capillary pressure. The following year, in 1993, he demonstrated that capillary pressure contrast between the matrix medium and fracture medium has a pronounced adverse effect on recovery performance. Form that time, several other researchers have used the same concept or a modification to represent the fracture capillary pressure. In 1994, Firoozabadi and co-workers suggested that if more fluid bridging were to occur across a horizontal fracture, one would expect more total flow to occur through the fracture. Therefore more even-tual recovery from a fractured set of rock having intergranular porosity is expected [5].

The purpose of this study is to clear up some of these uncertainties about the capillary continuity. Based on the field experience and experimental results, it is now clear that in most cases there exists capillary continuity between matrix blocks in reservoir condi-tions. The main questions are: how strong is that capillary continuity, and what are the controlling parameters for this phenomenon?

For a comparison of the production behave-our from porous media, the introduction of reduced dimensionless quantities is very convenient. In gravity-drainage experiments the characteristic flow rate can be taken as the maximum initial flow rate (q^*) of a vertical block with open top and bottom faces and without capillary retention of the oil, i.e.,

$$q^* = \Delta\rho_{og} . g . \text{ k. A} / \mu_o \quad (1)$$

To compare the free fall gravity drainage production curve, on a rational basis, the real time scale was made dimensionless by dividing the actual time (t) to the required time to produce all oil with a maximum drainage rate, i.e. characteristic time (T^*). For gas/oil system:

$$T^* = \frac{\mu_o \, \phi (1 - S_{wc}) L}{k . \Delta\rho_{og} . g} \quad (2)$$

$$t_D = \frac{t}{T^*} \quad (3)$$

Where T^* and t_D are the characteristic and the dimensionless time respectively, ϕ is the porosity, S_{wc} is the connate water saturation, and L is the length of the model.

Theory

The critical value of fracture thickness (t_{cf}) may be defined as the maximum value of fracture thickness that retains a stable liquid bridge. It is controlled by physical properties of a fracture, i.e., roughness, aperture, and fluids, i.e., density difference and interfacial tension between gas and oil. By assuming that, when a hanging drop touches the top surface of the lower block, it would be deformed to a liquid bridge, then the critical value for fracture aperture may be defined as the maximum size of stable-drop at that condition. The smaller the interfacial tension, the smaller capillary pressure will be which needs to be overcome by the weight of the droplet. Another point is that a drop does not fall because its weight is too great for the surface tension to support it, it falls because the "neck" becomes too long and narrow and contracts to one or several drops. If IFT is low the neck narrows faster. The number of secondary drops following the main drop depends on the size of the exposed pores and the magnitude of the interfacial tension. The formation of secondary small droplets reflects the dynamic effects of surface, gravity and viscous forces. The fracture capillary pressure may be defined as the pressure difference between non-wetting and wetting phases inside the fracture.

The capillary pressure contrast between the matrix medium and the fracture medium has some effect on recovery performance. In other words, when the capillary pressure of a fracture introduces a positive capillary pressure at the bottom face of the block, it acts as an external force and causes extra drainage of oil. In the following two cases based on the fracture aperture, an estimation of fracture capillary pressure has been presented.

a- For the case that fracture aperture is more than the critical value, i.e. $t > t_{cf}$, the drainage is mostly by formation and detachment of droplets. Assuming that oil drop is part of a sphere, its amount is equal to:

$$P_{cf} = (P_c)_{\mathrm{d}} = \frac{2\sigma}{r} = \Delta\rho \,.\, \mathrm{g.}\ (\mathrm{r}+\mathrm{d}) \qquad (4)$$

Where d is the distance between the drop center and the bottom of the block, which varies between 0 to t_c-r. For a typical case, i.e., when d ≅ 2r, the radius of the curvature can be calculated as:

$$\mathrm{r} = \left(\frac{2\sigma}{3.\ \Delta\rho\ .\ \mathrm{g}}\right)^{\frac{1}{2}} \qquad (5)$$

Based on the definition of critical fracture thickness, i.e. $t_{cf} = 2r$, it will be calculated as:

$$\mathrm{t}_{\mathrm{cf}} = \left(\frac{8\sigma}{3\ \Delta\rho\ .\ \mathrm{g}}\right)^{\frac{1}{2}} \qquad (6)$$

b- When $t_f < t_{cf}$, the drained oil is transferred through liquid bridge/bridges. In this case, by applying the Young-Laplace equation, the fracture capillary pressure is equal to:

$$P_{cf} = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \qquad (7)$$

Where r_1 and r_2 have opposite direction (sign), and it is likely that the liquid bridge has some sharp curvatures, while at the same time, P_{cf} be near to zero, i.e. $r_1 \cong -r_2$. It is obvious that the absolute value of fracture capillary pressure (i.e. pressure difference between gas and oil) for the liquid bridge is less than the maximum value of the capillary pressure at the drop (i.e. just before detaching). Therefore the absolute value of the fracture capillary pressure, without considering the influence of the lower block, is less than capillary pressure of a stable hanging drop.

In actual reservoir conditions, when the fracture aperture is more than t_{fc}, the effect of fracture capillary pressure on the gravity drainage process from the upper block is negligible and may be ignored. For the case of hanging drop it is more likely that the fracture capillary pressure is adjusted such that its value at the bottom of the block approaches zero.

Experiment

Apparatus. The experiments were performed using a stack of two homogeneous blocks in a very simple but perfectly characterized system. Free gravity drainage tests, using synthetic oil and air used as test fluids, were conducted at controlled room conditions. The porous and non-porous spacers were artificially constructed. Peripheral accessory equipment consisted of a vacuum pump and a balance interfaced to a computer for recording fluid production. A schematic view of the experimental set up is shown in Figure. 1.

Rock Properties. A number of outcrop sandstone cores and glassbead packs were used as rock models in this study. The porosity of models was measured by the saturation method. A Ruska air permeameter and the Darcy's set up were used to measure the permeability of the sandstone samples and the packed models, respectively. These values were corrected to an absolute permeability by using the Klinkenberg correction. After the air permeablity measurements were completed, a vacuum was applied to the top of the core holder for a period of about 24 hours. Oil was then allowed to enter the model through the bottom port. The mercury injection method was applied to measure the capillary pressure of the physical models (Figure 2), and their oil relative permeabilities were measured experimentally by the unsteady state process (Figure 3).

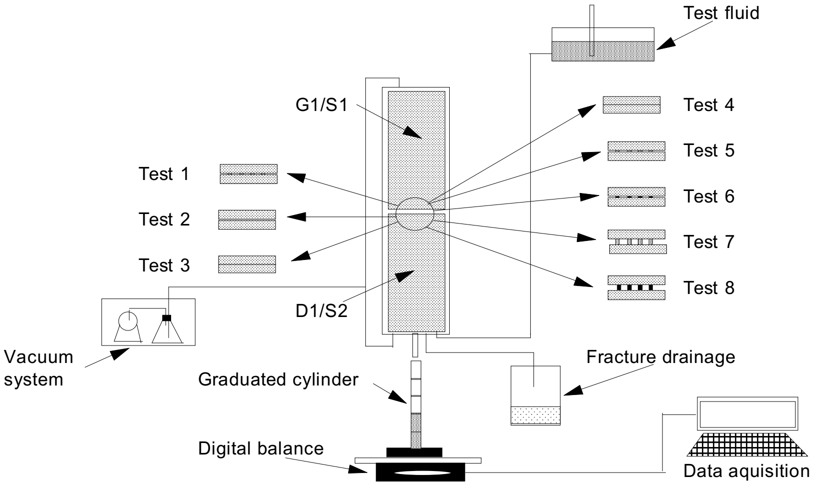

Figure 1. Apparatus schematic

Table 1. Physical properties of test fluids

Test Fluid	Density, gr/cc	Surface Tension, mN/m	Viscosity, cp
Air	$1.2*10^{-3}$	-------	0.018
Oil	0.842	30.50	6.20

Test Fluids. Synthetic oil was employed as oil (wetting phase) in all gravity drainage experiments and air was used as gas (non-wetting phase). The physical properties of test fluids are given in Table 1. In transparent models, oil was identified by a red colour (dyed by Sudun).

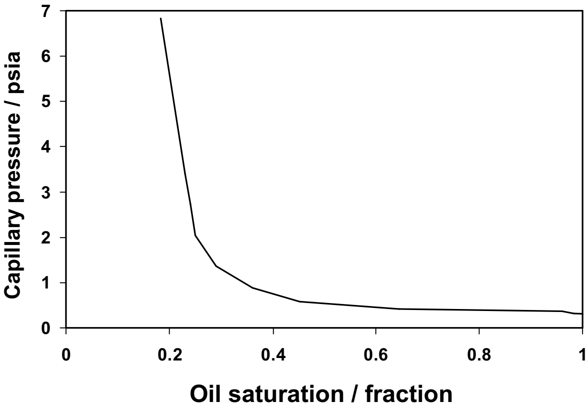

Figure 2. Capillary pressure of sandstone model

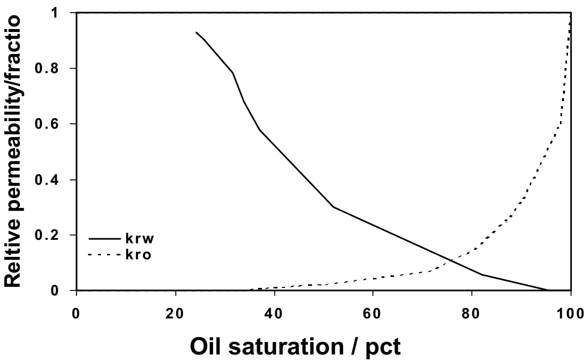

Figure 3. Relative permeability of sandstone model

Experimental Set-up. Two sets of experiments were performed: one with a stacked glassbead pack 29.5 cm long block over a dead (impermeable) 29.5 cm long block, and the other with a stack of two sandstones 33.5 cm and 38.2 cm long blocks on top of each other.

Stack of a glassbeads pack block over a dead block. Three types of free fall gravity drainage, (FGD), experiments were carried out with block G1: 1- Porous spacers in the fracture space between the blocks (i.e. Tests 1a and 1b); 2- Fully open fracture (Test 2); and 3- Direct contact between two blocks (Test 3). The goal was to identify the effect of horizontal fracture on recovery from the upper block. The top block (G1) is a glasspack cylindrical model with high permeability (42 D) and high porosity (33.9 %). This medium is very homogeneous, and the high permeability gives a rather fast gravity drainage process. Due to the narrow distribution of the grain size (210-280 μm), the plateau of the gas front is flat. To cancel the effect of the lower block, a non-porous metal block "D1" was used with the same dimensions of the upper block. With the test fluids, the threshold pressure corresponds to a 7.20 cm height of the liquid column.

The blocks G1 and D1 were placed in a transparent cylindrical core holder filled with oil, which has the boundary diameter 5 mm more than block G1. The experiments started after draining all external oil from the fractures and dead volume inside the core-holder. The amount of draining oil, collected in a graduated cylinder positioned below the core-holder on top of a high precession balance, was recorded as a function of time with a precision of 0.001 gr. To have the same initial condition after each experiment, the model was taken apart and treated in such a way that the wettability should be the same for all experiments. The block was saturated with the oil. The maximum gravity drainage rate of the model was calculated to be equal to 1.64 cc/min.

Tests 1a and 1b were conducted by using four aluminum shims (2 * 2 mm), each with a thickness of 2 mm between two blocks which provided a horizontal fracture with a 2 mm aperture. Test 1b is a duplicate of Test 1a. The reason for performing two experiments exactly at the same conditions was to investtigate the repeatability of the experiments, and to see the influence of experimental error on the recovery curve (Figure 4). The small difference between the ultimate recovery for these two duplicate experiments (i.e. 0.0011 pv) shows the amount of uncertainty of the experimental results. To provide a fully open fracture in Test 2, the upper block was suspended by a hanger just 3 mm above the top surface of the lower block. In the last test (Test 3), block G1 was placed directly on the top of the non-porous block, and to ensure full contact, a heavy weight was put on the top of the upper block.

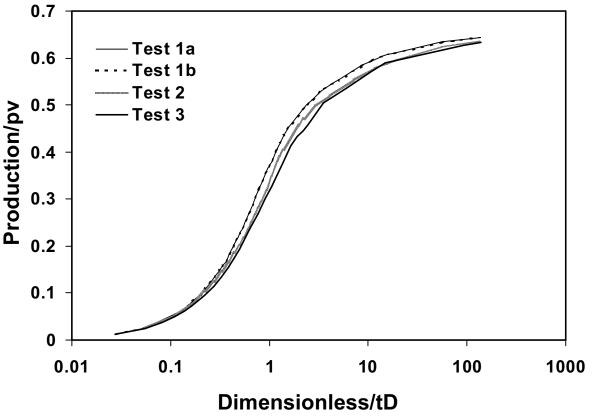

Figure 4. Oil production vs. Time (log scale) for gravity drainage of stack of blocks G1and D1.

Stack of Two Sandstone Blocks. A stack of two homogeneous rectangular sandstone blocks (S1, S2) with block heights equal to 33.5 cm and 38.2 cm respectively were used. The sandstone rock used for these tests is from the outcrop, with a permeability of 0.75 darcys and porosity of 22%. The sandstone rock is homogeneous and the plateau of the capillary pressure curve is approximately flat and ranges over a wide saturation zone. The blocks were placed in a container of oil, which had a boundary dimension of 4-mm more than the stack-block. At the test conditions, the threshold pressure corresponds to a 30.35 cm height of the oil column, which means a matrix block shorter than 30.35 cm will not give any recovery by gravity drainage. At the equilibrium, the average oil saturation behind the gas front (above the threshold height) was equal to 47.5%. The maximum gravity drainage rate of blocks was calculated as 3.46 cc/hr.

Five types of experiments were carried out: 1- Full direct contact between blocks; 2- Four 2*2 mm porous spacers, each with a thickness of 0.5 mm; 3- Four aluminum shims (2*2), each with a thickness of 0.5 mm; 4- Four 2*2 mm porous spacers, each with a thickness of 2.6 mm; 5- Four aluminum shims (2*2), each with a thickness of 2.6 mm. Initially both blocks were saturated with oil and all five tests were performed at room conditions. Fractures surrounding the matrix blocks were initially filled with oil. The rapid drainage of oil in vertical fractures left a thin layer of oil film over the vertical boundaries.

The main goal of performing this series of experiments was to identify the effect of type and thickness of spacers on capillary continuity between blocks and the gravity drainage performance. The physical properties of the blocks and type of contact for each experiment are shown in Tables 2 and 3.

Results

Stack of Blocks G1 and D1. The specifications and results of experiments are given in Table 3. The oil production (fraction of initial oil in place) as a function of the dimensionless time (t_D) is plotted for each test (Figure 4).

When four 2 mm thick spacers were used between the blocks (i.e. Tests 1a and 1b), the produced oil volume and drainage rate were

Table 2. Physical properties of cylindrical models

Models	Dimensions, cm	Porosity %	Perm. (D)	T*- min	q* -cc/min calculated	Fluids
G1♥, ♣	R=1.250, Z=29.50	33.90	42.376	29.75	1.65	Oil /Air
D1*, ♣	R=1.250, Z=29.50	-	-	-	-	-
S1♠	X=3.311, Y=2.953, Z=33.5	22.12	741	12.29	3.450	Oil /Air
S2♠	X=3.329, Y=2.950, Z=38.2.	22.25	762	23.52	3.466	Oil /Air

♥ Transparent model ♣ Cylindrical models
* Dead model ♠ Cubical models

Table 3. List of experiments

Experiment no.	Ultimate recovery (pv)	Fracture/Spacers	Test Duration (min)
Test 1a	0.644 (0.6444)	Four porous spacers (2 * 2 *2 mm)	2465
Test b	0.643 (0.6433)	Four porous spacers (2 * 2 *2 mm)	2465
Test 2	0.637	Open fracture (3 mm)	2465
Test 3	0.634	Direct contact between two blocks	2480
Test 4	0.325	Direct full contact	31300
Test 5	0.323	Four 2*2*0.5 mm, porous spacers	33201
Test 6	0.322	Four 2*2*0.5 mm, metal spacers	33100
Test 7	0.237	Four 2*2*2.6 mm, porous spacers	32130
Test 8	0.225	Four 2*2*2.6 mm, metal spacers	32100

at their maximum values. While, when there was full contact between two blocks (i.e. Test 3), the oil production and flow rate were at their minimum amounts. For the case of open fracture (i.e. Test 2), the amount of oil production is between the two extremes (i.e. Tests 1 and 3). The reasons for this difference are:

1-Due to the existence of porous spacers, the fracture thickness is added to the effective block height, which results in the highest value in oil recovery for Tests 1a and 1b.

2-For the cases of direct contact (i.e. Test 3), the fracture capillary pressure may be assumed equal to zero. In this case, the oil recovery is only controlled by the physical properties of the matrix block without any boundary effect from the fracture side.

3-When there are liquid bridges inside the horizontal fracture, there exists a small pressure difference across the interface of the liquid bridge (i.e. fracture capillary pressure). Although the capillary pressure inside the fracture is near zero, it is more likely to have positive capillary pressure at the bottom face of the upper block. The positive capillary pressure at the bottom surface acts as an external force and results in some additional oil drainage from the block. In this case, the capillary pressure of the fracture will cause some reduction in threshold height of the upper block.

Since the drainage rate and recovered oil volume for the 3 mm open fracture is less than 2 mm spacers, this shows that the effect of the amount of positive capillary pressure at the bottom face of the block is less than $\Delta\rho.g.t_f$ = 172 dynes/cm^2 or 0.0024 psi (t_f is fracture thickness).

Stack of Two Sandstone Blocks.

***Test 4: Blocks in direct full contact*.** Figures 5a, 5b and 6 show the cumulative oil production and flow rate data versus time. During the time interval (0-30 min), the production rate is more than the calculated characteristic drainage rate (i.e. 3.46 cc/hr). The difference is caused simply by the film flow of the oil, which was initially over the boundary surfaces of the upper block. The rapid drainage of oil in vertical fractures left a thin layer of oil over the vertical boundaries of the blocks. During the time interval (300-3000 min), the recovery rate decreased sharply from 4.31 to 0.37 cc/hr, i.e., a transition period from mainly bulk flow to mainly film flow process. From the time 3000 min, the slope of the flow rate curve becomes flatter, i.e., the front has reached the threshold height and the drainage is mainly by film flow from the two phase region. At the end of the test (31300 min) the oil flow rate is 0.00175 cc/hr, and after this time, one can see that the production is still continuing by the film flow process. An increase of 0.02 gr was observed in the weight of the receiver in the following 50 hours.

***Test 5: Four 0.5 mm porous spacers*.** In this test, four 0.5 mm thick (2*2*0.5 mm each) porous spacers were inserted in the fracture space between the matrix blocks. The ultimate recovery of this experiment is close to that of Test 4 (Figures 5a and 5b), which shows that, there exists a good degree of capillary continuity between two blocks. The delay time in the production curve compared to that of full contact shows some restriction in oil transmissibility through the fracture. The test was stopped at 537 hrs. Although it is not clear on Figures 5a and 5b, our careful measurements showed that there was some flow of oil during the time interval of 537-960 hrs.

***Test 6: Four 0.5 mm metal spacers*.** This test is the same as test 5 except that four 0.5 mm thick (2*2*0.5 mm each) aluminum shims were used instead of the porous spacers. There is a good match between the recovery curves of this experiment and Test 5 (Figures 5a and 5b). It shows that, although the spacers are impermeable, the fracture width is small enough for having stable liquid bridges and capillary continuity. The oil transmis-sibility through the porous spacers has a small role in the drainage process compared to that of the liquid bridge. The small delay time in production compared to that of Test 5, is due to the spacers which reduce the overall transmissibility.

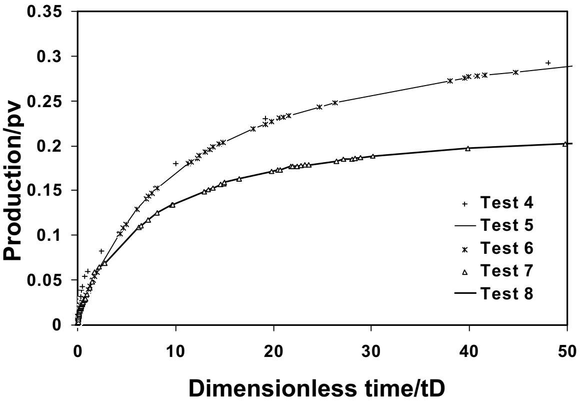

Figure 5a. Oil production vs. Time (linear scale) for stack block S1 and S2

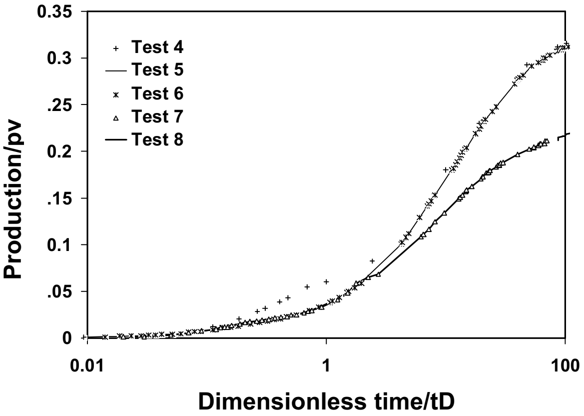

Figure 5b. Oil production vs. Time (log scale) for stack of blocks S1 and S2

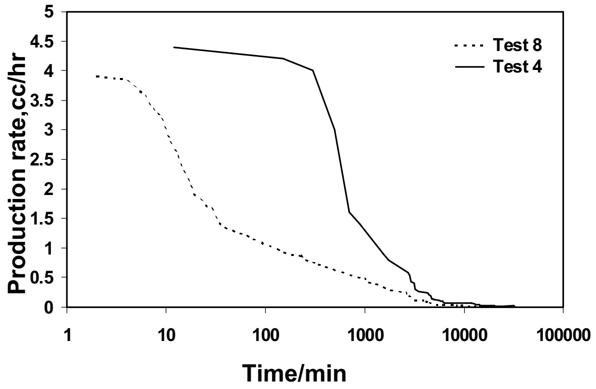

Figure 6. Production rate vs. Time (log scale) for Tests 4 and 8

Test 7: Four 2.6 mm porous spacers**.** This test is similar to Test 5 except that the thickness of the porous spacers was increased to 2.6-mm. The oil recovery is severely slowed down as compared with Test 4 (Figures 5a and 5b). The experiment was stopped arbitrarily at time 60.5T*, (after 9 days), at which the production was still going on at a small rate. The measured saturation at the end of the test indicated that for the lower block, the oil saturation was equal to its residual value, and due to negligible capillary continuity, the oil saturation in the upper block was only slightly less than its threshold value.

Test 8: Four 2.6 mm metal spacers**.** This test is the same as test 6 except the thickness of the aluminum shims was increased to 2.6-mm. As expected the oil recovery of this experiment, compared to the other four tests of this series, has the lowest amount (Figures 5a and 5b). Due to a high fracture thickness, liquid bridges cannot be formed. The oil saturation of blocks at the end of the test is slightly less than the residual value, i.e., saturation that is determined by balance between gravity and capillary forces in each block. The experiment was stopped at time 150T* (after 22.4 days), while oil was still flowing at a very small rate (0.007 cc/hr). This very small oil flow rate is attributed to the oil film around the metal spacers.

The production rate versus time for Tests 4 and 8 is shown in Figure 6. The oil film flow rate at the end of this test is about five times more than that of Test 4. This contrast is caused by the difference in the amount of oil saturation in the upper block. In this test about 80% of the pore volume of the upper block is saturated with oil, and the only restriction for oil flow from the upper block to the lower block is transmissibility of oil film around the spacers. At the end of Test 4, the saturation of the upper block was at its residual value, i.e., there was no threshold oil zone.

Discussion and Concluding Remarks

a- The results of the experiments of stacked blocks G1 over D1, revealed that there exists a critical fracture thickness for each set of physical conditions of the fracture system. When the fracture aperture is more than the critical value, there would be no capillary continuity between blocks and the drainage takes place by formation and detachment drop pro-cess. In this case the pressure difference between gas and oil in the horizontal fracture (i.e. the fracture capillary pressure) is governed by the radius of the curvature of the hanging drop. The hanging drop has two ef-fects on the drainage performance of the upper block, i.e. by its length and by its capillary pressure. The com-bination of these two effects (which have different sign) would be such that at the bottom surface of the upper block, the capillary pressure has a very small value. This value can be calculated as $P_{cf} = P_{cd} + \Delta\rho.g.t_c$, where P_{cd} and t_c are capillary pressure and length of the drop, respectably.

When the fracture aperture is less than its critical value, the enlarging drops deformed to stable liquid bridges between the upper and the lower blocks. For the case of a dead lower block, there is no capillary continuity between blocks and the existence of a liquid bridge may induce some positive capillary pressure at the bottom surface of the upper block. This positive capillary pressure acts as an external force and has a positive effect on gravity drainage performance from the upper matrix block. When the lower block is impermeable, the amount of fracture capillary pressure (both for the liquid bridge and the hanging drop) compared to the capillary pressure of the matrix block in an actual reservoir condition is negligible.

b- The main parameter that must be considered in capillary continuity is the 'drainage duration'. By increasing the degree of capillary continuity between two blocks, the starting time of shifting from bulk-flow via the liquid and/or porous bridge, to film flow over and/or through the spacers, will be increased.

c- In a stack of interacting, equal and oil saturated blocks, which is surrounded by gas, the oil produced from the upper blocks travels through the complete stack before being produced at the bottom of the lowest block. For the case of non-capillary contact between the blocks (thick fracture), the total amount of ultimate recovery will be equal to the number of blocks times the ultimate recovery of a single block. But for full capillary continuity between blocks, the performance of a stack block is like that of a single block with the same height.

d- When the fracture aperture is thick, the oil will drain mainly by film flow process. The film flow process over the non/less porous spacers cannot provide adequate liquid transmissibility for flow across the fracture between the matrix blocks. The oil transmissibility by film flow is so small that the production of oil from the threshold zone of the upper block will take an extremely long time. Since the drainage flow rate by film flow is very small, this kind of capillary continuity is recommended to be considered as non-effective. When the fracture aper-ture is small enough for the existence of stable liquid bridges, the draining oil flows through them as bulk flow. Based on high transmissibility via liquid bridges, it could be considered as effective continuity. There still exists some delay time between the recovery performance of a stack block with the effective capillary continuity compared to that of a single block with the same height.

e- When the lower block is porous and permeable, if during its enlargement process the oil drop attaches to the upper surface of the lower block (i.e. a narrow fracture), the pressure difference between oil and gas changes suddenly. The capillary pressure of the fracture (i.e. capillary pressure of liquid bridge) will be comparable with the capillary pressure of the matrix at that elevation. The two radii of the curvature of the liquid bridge would be adjusted such that they represent a capillary pressure, which is a function of density difference between oil and gas and the height of the fracture from level of zero capillary pressure. Therefore, when the continuity between matrix blocks are through the stable liquid bridges, as long as the fracture aperture is less than its critical value, the capillary pressure of the horizontal fracture has no relation with the amount of fracture aperture. In this condition fracture capillary pressure can be calculated from the equation $P_{cf} = \Delta\rho.g.h$, where h is the elevation of the horizontal fracture from the level of zero capillary pressure.

f- For a stacked block, when there is no liquid bridge between the blocks and spacers are non-porous, the fracture capillary pressure may be considered as zero (i.e. discontinuous blocks). While when there exist liquid bridges between the blocks, the fracture capillary pressure will be equal to the capillary pressure of the liquid bridge. There exists a maximum P_c, of the liquid bridge such that beyond this P_c the liquid bridge will disintegrate. If the capillary pressure at the top of any matrix block exceeds this value, the liquid bridges that contact the adjacent matrix block will disintegrate and capillary continuity will shift to discontinuity.

g- Further research is needed to quantify the maximum capillary pressure of the liquid bridge just before disintegration.

Nomenclature

k	permeability, L^2, md
P_c	capillary pressure, m/Lt^2, kPa
P_{cf}	fracture capillary pressure, m/Lt^2, kPa
$P_{c\text{-}lb}$	capillary pressure of the liquid bridge, m/Lt^2, kPa
r	radius of curvature
$S*$	normalized saturation
S_g	gas saturation
S_o	oil saturation
S_{or}	residual oil saturation
t_D	dimensionless time
t_f	fracture (thickness) aperture
σ	surface tension, m/t^2, mN/m
μ_o	oil viscosity
ρ	density, m/L^2, g/cm^3

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