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Study on EOR Mechanisms by Microbial Flooding

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ABSTRACT

We have carried out flooding test with cores, sandpack, pore level model by microbe NG8O, special metabolic products (G01, 002,003) under reservoir temperature. The results are: (1) Microbes migrated through core pore and fermented in it; microbial concentration has an increasing trend, part of cells was absorbed on sand surface. (2) Oil recovery that flooded by bacteria with concentration 10% is over 6% higher than in water. (3) The highest recovery is 13.8%, flooded at best flooding mode, NG8O products and its constitute; (4) The earlier the time of injecting fermented broth, the better the result obtained; (5) Metabolites bear effect of denudation on oil films; and metabolisms result in alteration of wettability, in which a special biochemical process and "in situ growth" effects characterized by bacteria take place; (6) Mechanisms observed in the pore level model during microbial flooding are: starting residual oil re-flowing by emulsification-carrying, changing the wettability, denuding oil films and producing "Jamin Effect" in the pores while flooding. We performed microbial flooding program in G69 block, which has 5 injections wells and 7 drainage points. Mixed original, NG8O, 80 and DG2, fermented broth 720m^3 was injected in with three slugs during March to July,2019. Monitored preliminary results show that the decline trend of the block oil production was controlled and some wells' production began to increase. That the mechanism of microbial flooding in the oilfield improves producibility.

Keywords: Flooding, Microbial, Bacterial, Oil recovery, Wettability, reservoir temperature

INTRODUCTION

Enhancement of oil recovery is critical for mature fields. EOR by microbial flooding becomes a focus among producing countries because of its cost effectiveness, wide applicability, easily operability and non-damaging to formation and environment [1, 2, 3, 4]. Microbes with hydrocarbons as carbon source can enhance oil recovery by biological and biochemical effects. More specifically, microbes in a reservoir can grow to improve oil properties, and meanwhile, the metabolically beneficial products modify the solid and liquid phases to increase oil mobility. However, picking the right microbe candidate is key. Many pilot tests turn out that this is significant, and further study is required on the mechanisms.

This paper testifies the microbial displacement mechanisms in a pilot laboratory simulation of G69 block, including interaction of microbe with oil in porous media, microbe growth and migration, effect of metabolic components and concentrations on EOR. Flow mechanisms were observed in pore level model.

Reservoir condition and fluid property

G69 is a small fault block of the Akata/Agbada depression of the Niger Delta (Fig.1). The principle reservoirs are Paleogenic zones 1801.3-1960.Om deep and at 73 ^{0}C in average. The estimated OOIP is 1,920,000 t within an oil- bearing area of 1.19 km2. The processed production water (shown in Table 1) is injected. The dead oil density is 0.8801g/cm^3, pour point 42.4, wax content 24.5%, colloid and asphalt content 24.84%, in-situ oil viscosity 6.8 mPas. There are inter-layers of sandstone and limestone that make up sealed reservoirs with simple structure but good communication.

The block was first developed in 2004 and injected in 2005. Productions were initially high but declined soon after. By March 2012, there were 8 producing wells with average daily output of 7.9 t per well and 5 injection wells. Water cut was about 91.2% and the recovery was 22.1%.

Experiment Conditions and Methods

Test Condition. The reservoir fluid and displacing microbe in the 069 block is used in the lab test. An average water-front advance rate of 5m/d is taken as flood rate determined by radioactive isotope survey. The test is undertaken at 73^0C and the involved microbe is thermophilic N080 which was chosen for the field pilot. The inorganic culture medium is formulated by injection water, including NH_4 CI, K_2 HPO_4 and so on.

Models: Two artificial cores are used. One is consolidated by quartz and aluminium phosphate and then sintered, with a size 40x2.4x4.4cm (LxWxT), permeability 0.4-0.6 um2. Another is sand-packed with filtered oil sands and also with water and oil added in. Its size is (DxL) 2.5x30 cm, permeability 1.1-1.6 um^2, average initial oil saturation 62.4%.

Additionally, a micro simulated glass model is photoetched based on a model plot prepared with the pores network of a G69-4 well core slice. But the modeled pores and their throats are amplified about 5 times. The max pore diameter is 800 um, the mm 8 •m, permeability 03-06 . m^2.

Physical simulation test on cores:

Migration and fermentation. At laboratory temperature, fermented broth of microbe ($2x10^8$ cell/m1) is injected into the sand-packed tube core. The bacteria concentration at tube outlet is monitored and the cell migration is observed, in fermentation test, the same quantity of bacteria is put into bottles both holding culture medium but with and without layer sands (simulating loose porous medium).

The bottles are shaken at constant temperature and the concentrations surveyed continually, correlations and observations on the growth and fermentation are made.

EOR test: Under the same condition, EOR by bacteria flooding and water flooding are compared. The NG80 microbial flooding has two groups as following.

Microbial flooding at original: Under initial oil saturation condition, a volume of I PV NG80 fermented broth at 10% concentration is injected and kept at lab temperature for 7 and 14 days to make them grow, ferment and metabolize. Then after interaction with residual oil, 4 PV water is flooded and recovery is calculated.

Microbial flooding at current water cut: Under current water cut 91% (at first water flood about IPV) in the G69 block(April 2000), 1 PV of NG8O is injected and kept for 7days and then 3 PV water is flooded (the total displacement 5 PV).

Effect of metabolites on test. Influence of biosurfactant and organic acid, metabolic products, on recovery is evaluated with bacteria (GOl, G02) fermented at 37 • 5 PV displacements at different concentrations were made.

Influence of biogas on recovery is tested by measurements of displaced oil and pressure variation 7 days after the gas-producing bacteria (G03) is injected
into the sandpack.

Influence of microbe metabolites on recovery is conducted by 5 PV flooding and then the whole test is completed.

Pore level displacement event simulation test: In this test, some filtered produced water is made nontoxic blue or leuco and the dead gas from G69-8 well with some kerosene added is made neutral red for easy observation. NG 80 is selected. After injection the model is maintained at 73. and is displaced at 30.(room temperature). The test for the model takes the following procedure — evacuation and saturation with water, water displacement by oil and saturation with oil, oil displacement by water, microbe injection at constant temperature, restoration of oil displacement by water, monitoring data and recording the steps (photos).

TEST RESULTS AND DISCUSSIONS

Physical simulation test of microbial flooding

Microbe migration in porous medium

In the sand-packed tube model, in-situ oil saturation adapted is 25% and water saturation 15%. A wholesale bactericidal process is carried out for the model and test flow system. Before test, the model is evacuated and saturated with produced water, then connected to the flow system. Original fermented broth was injected into the model. At the model outlet, samples are taken. The microbial concentrations are continually monitored until no magnificent change is surveyed. Then produced water is injected to displace the microbe fluid until there is no big concentration change and end the test. See Fig.2 for test results [5].

The cells show a strong absorption on rock surface as the microbial concentration at outlet reaches its balance after injection of 2.6-2.8 PV. Injected at two rates, the injection volumes differ only 0.2 PV when measured at outlet, indicating little effect of rate on microbial volume required for absorption balance. Cells can still be detected at test-close when water injection is 9.5 PV, presenting microbial absorption and de-absorption.

The cell fermentation in porous medium

The original fluid is diluted to 10% by culture medium (concentration at $2x10^7$ cell/m1) and displayed-separately in 4 cone bottles in each of which there is 150 ml of culture. 100g reservoir core sands are placed into two bottles to simulate loose medium. The other two are used only for cell culture. All these have been processed with a bactericidal action before inoculation. After inoculated with the same quantity for each bottle, they are sealed and shaken in a high-temperature water bath. Every day, samples are taken for concentration survey until its balance. Results are shown in Fig.3. The data for the first day showed some decline, indicating bacterial absorption on sands. In the later data, the concentrations of the two cultures increase almost in parallel, only that cell growth in the sands delays I or 2days, but the final concentrations are nearly same, indicating that sands do not affect final bacterial concentration.

Test for EOR by NG 80 flooding

Flooding simulated water cut

Bacteria NG 80 was flooded in the G69 block pilot. It produced surfactant, organic acid and biological gas. The surfactant turned out applicable to the block conditions (6). Microbial flooding test with actual water-cut simulation of current G69 block was conducted to make comparison of enhanced recoveries by NG 80 and water flooding. When the block shows a water cut 91%, in test, at first, flood water to displace oil until outlet water cut becomes 91% (water injection about 1PV), then inject IPV of fermented broth at 10% and closed both ends of the model. It was kept at laboratory temperature for 7days, water flooding of 4 PV, -then test is terminated. Results in Fig.4 show that microbial flooding can enhance oil recovery by 6.6%.

Timing of bacteria injection is studied. Initially IPV of NG 80 at 1% is injected and kept at formation temperature 73 ^{0}C for 7 and 14 days respectively to allow cells grow, ferment and interact with residual oil. Based on interaction time the minimum fermentation period and relation of bacterial stay time in core and EOR can be determined. It turned out that 7 days were not enough. Better recoveries required up to 10 days (Fig.4).

Effect of metabolites on recovery: There are quite some metabolites. It is necessary to confirm which one principle ones and their contribution to recovery. Microbial metabolite is mainly biologic surfactants and organic acids. Some bacteria that mainly produce surfactant (GO 1 at 1500 mg/I) and acid (G02 at 33000mg/I) separately are selected and fermented at 37 ^{0}C to displace oil and evaluate its concentration effect on recovery. Results are collected in Fig.5 and Fig.6.

Biological surfactant affects. The test indicates that recovery enhancement margin rises along elevating metabolite concentration. The best enhancement improvement was at 10.5%. When below 1000 mg/I, EOR is improved by 6.5%; when above that, 9.4%. This is possibly caused by reduced surface tension at lower surfactant concentration. Organic acid affect Recovery of oil displaced by acid at max concentration can be 6.4% better than that of water flooding. Enhanced recovery margins based on oil

displacement plot with acid at 10,000 mg/I make no apparent difference, indicating that acid concentration does not influence oil recovery proportionately, but some intermediate metabolites and their dissolution in oil help enhanced recovery which cannot be expected solely by improved permeability due to acid-dissolved rock.

Biogas effect: The bacterium G03 whose gas-producing ratio is 14.6% is chosen for test of biogas (C02) effect on recovery enhancement. Results summarized in Table 2 imply that biogas application can improve residual oil recovery by 1.6%, or 0.6% when converted to initial oil recovery.

NG 80 bacterium metabolites Biogas effect on recovery: Oil recovery by NG 80 metabolite displacement is 9.2% high than water flooding. Injection of IPV NG 80 at 10%, maintaining for 7 days and then put in 4 PV NG 80 will enhance recovery margin by 13.8%. In fact there are two effects attributing to the recovery—bacteria and metabolites. This is 4.6% better than a single process of NG 80 displacement recovery.

Microbial flooding test in pore level model:

In residual oil condition, 1 PV of NG 80 at 10% is injected into the model with two ends closed. It is kept at lab temperature for 7 days. Record the pore level model displacement events with a video camera. Three flow mechanisms were observed.

Mechanism One: emulsify-carry, initiate move of residual oil. The model is water wet, so in greatly water- flooded pores, bacterial fluid surrounds oil droplets or small oil intervals already isolated by water to make cells grow and metabolize. In the pores with a lower level water flood, bacterial fluid cannot flow freely, but covers oil (mostly small intervals) along water films that it absorbs upon. Moreover because of dilution by irreducible water bacterial concentration is lowered further[7].

Under the biological and biochemical effects, the degraded oil emulsified and formed into droplets, which were extended, deformed and flowing [81(Fig.7).

After water driven, residual oil degraded by bacteria and in small intervals was initiated for its slow move out of pores, as can be observed in dramatically water- fooded pores. The emulsified fluids meet relatively small resistance through pores and the active cells deposited on pore surfaces reduce more resistance.

Mechanism Two: **Dibond oil film.** As a result of heterogeneous wettability the pore surface and effects of heavy components, some oil is retained on pore walls.

With bacterial functioning, the oil is moved by water flow. Under microscope, it is observed that the oil is disbonded, oil film thinned then separated as a thread (Fig.8).

Mechanism Three: Biogas "Jamin Effect". Bacterium NG 80 produces 5 ml gas per 100 ml fluid. A specialized lens was applied for test in a modelled pore saturated with cell fluid. The pore center is all red oil surrounded by bacterial fluid. The model is put in a constant temperature cabinet. After 96 hours, tiny gas bubbles break from the bottom and gradually become bigger. At 145 hour, they turn to small ones, but stop further growth after 175 hour (Fig.9).

There are two gases with biological origins—movable and unmovable gas produced by bacteria. Movable gas joins fluid flow and is affected by pore structures. In pores with larger pore-throat ratio, movable gas has a poorer mobility, so more accumulative. Oil mostly accumulates around gas bubbles and slides forward and disbonds along gas bubble surface, therefore providing little resistance. As a result of Jamin effect, unmovable gas makes itself resistance to water percolation in the in the middle part of pores even, redirects flowing.

In simulation on second water flooding in a heterogeneous model, unmovable gas in big pores acts as resistance to water flow, forcing water and fermented fluid flow to less permeable areas. This is a micro-scale profile control. Movable gas during flowing process incorporates or separates, and so changes micro swept- volume.

The pictures show that the recovered percentage in permeable areas is about 83%, in poorer ones 51%. There still exists concentrated residual oil never swept. In high flooding volume conditions, recovered degree is better, 78% in average,

Disbond oil film on oil-wet surface by bacteria "growth in situ: "Bacterial "growth in situ" refers to its process and metabolites effecting on oil film for separation during bacterial growth period. The disbonded

film .area versus cell growth time is illustrated in animation in Fig.10. Both observation and simulation show that the disbonding process starts in some local places and expands with time. Apparently, oil film extends like a circle in plain. As the film has some thickness, it extends in triangle if observed from the side (Fig.11).

When bacteria are interacting in group, they seem to expand like circles, but on the side they expand in layers, resulting in layered disbonds of oil. This is because bacteria on-location growth produces concentrated surfactants in some places and makes solid surface trend to water-wet.

Microbial flooding test.

Test plan. The plan was prepared based on reservoir engineering, laboratory experiments and simulations results.

Injection wells. Five water injection wells are taken for bacteria injection,

Beneficial wells. There are 7 wells responding to the injections. Except 69-19 well producing by a rod pump, the others are equipped with electric pumps. This well group area is 0.385 km2. OOIP 730,000 tons in formation volume of 1,440,000 m^3.

Slug design. It is planned to inject 700 m^3 with each well injection showed in Table 3. The bacteria are combination of NG 80, 80 and DG 2 with different functions.

Slug concentrations. Simulation indicates enhanced oil recovery at 4-6% injection concentration. Taken into account of diluted bacterial injection front and end by water, the slug is planned to be in 3 stages. The first stage takes 8'/, the main slug 6%, the last 8%.

Culture medium. Culture medium slugs are added both before and after bacteria injection for better fermentation.

The medium components mainly include nitrogen, phosphorus, potassium and minor elements etc.

Forecast test. The pilot test was carried out between March and July 2019. It made EOR 3.6% (OOIP).

Test preliminary effective. Up to Feb. 2020 production decline trend of the block was restrained (Fig.12). Some of wells (We1l69-19,Fig.13) began to witness increased production. Water cut was controlled or dropped. Crude properties were also improved, wax content decreased 3.4%, colloid and asphalt content decreased 3.6%. The test is only preliminary, dynamic data is being monitored.

CONCLUSION

1. Bacteria can grow in porous media and with fermentation its concentration can be raised by an order, specifically, from initial $2xl0^7$cell/ml to $1.2xl0^8$cell/ml.
2. Microbes can move along with water through pore throats. The bacteria make strong absorption and de metabolic absorption on rock surface.
3. NG 80 can produce a great deal of metabolites which help improve oil property and enhance recovery by 6.6% in flooding simulation with actual water-cut involved. The recovery is enhanced 9.6-10% better than water flooding in test of bacterial injection under condition of initial oil saturation. This indicates that injected water dilutes bacteria fluid and reduces its effects.
4. Bacterial single metabolite and NG 80 metabolites displacement tests show that main factors affecting recovery are type and concentrations of biosurfactant. The best EOR is supposed to obtain from the optimum mode of injection bacteria fluid without water flooding at first and then metabolites working for additional displacement.
5. Pore level displacement events experiment appear that in water-wet micro- model oil displacement, microbial EOR mechanism involves emulsifying, carrying, disbanding oil-film and biogas "Jamin effect". Growth in situ prompts solid surface from oil-wet transfer to water-wet.
6. The preliminary test effective justified that microbial displacement can enhance oil recovery, in that the applied bacteria are appropriate for the layers.

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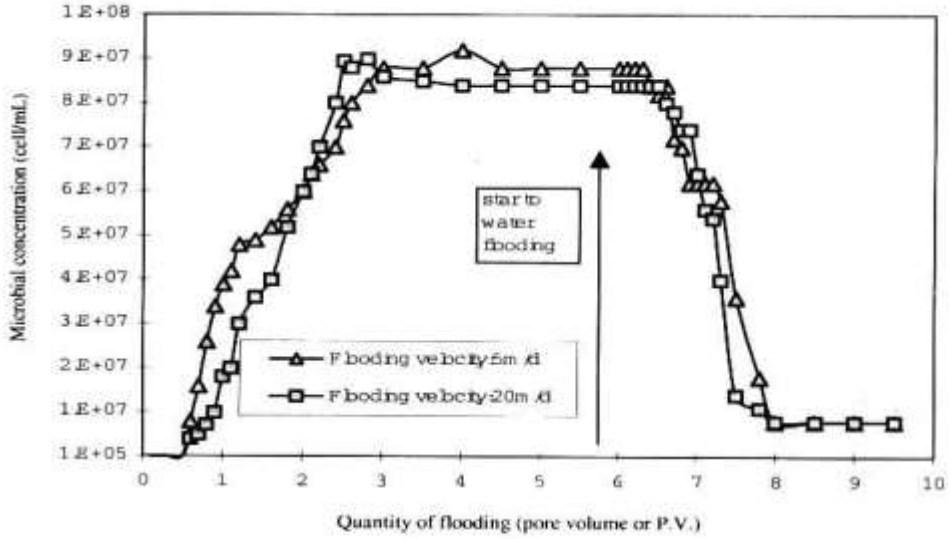
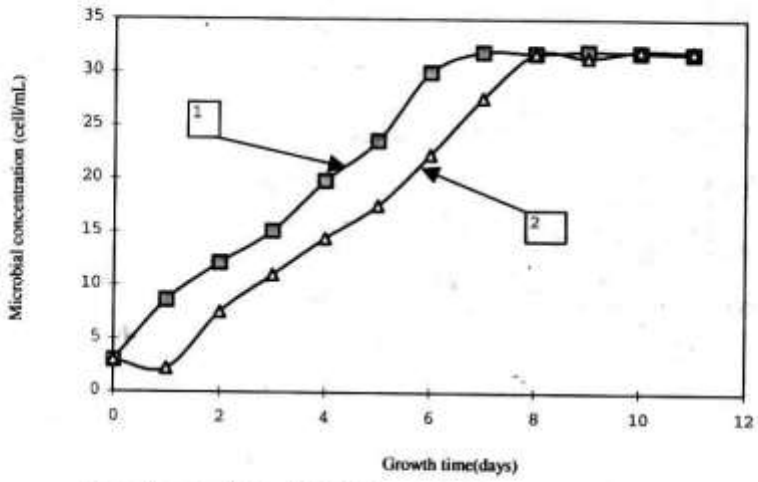


Fig. 2 Microorganisms migrated through pores of sandpack at two flooding velocities



1-microbe cultured in the flask which contain half of reservoir sand;

2-microbe cultured in the flask which did not contain of reservoir sand;

Fig. 3 Microorganisms growth in shake flask

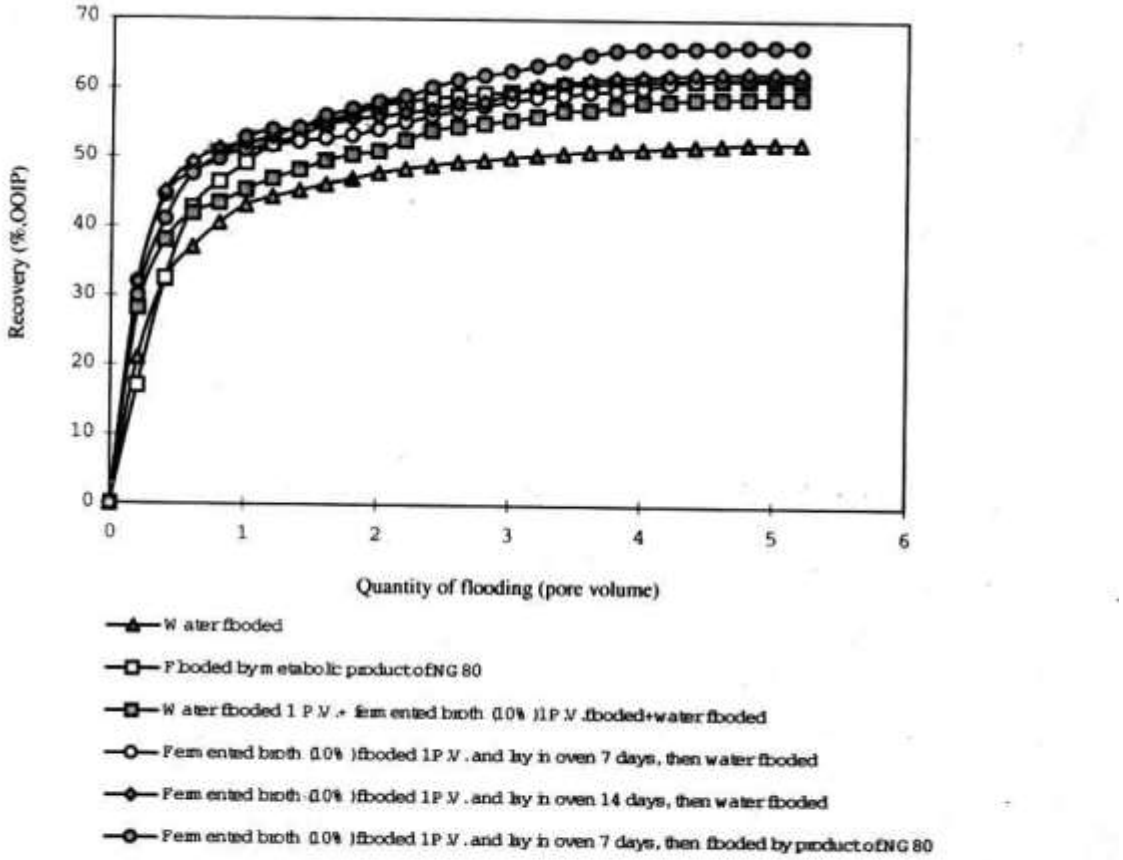


Fig. 4 Recovery effected by injecting mode of different fluid

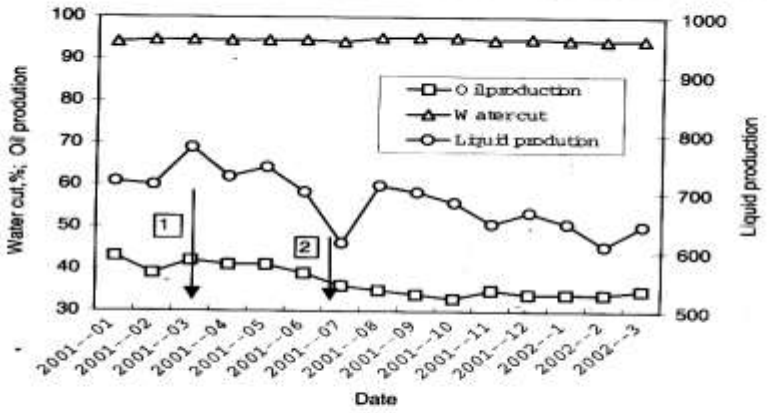


Fig.12 Production curve of G69 block
1-Start to microbila flooding; 2-Water flooding

Table 1 Properties of Injection Water of G69 Block

Name of Ions	K^++Na^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	TDS
Concentration, mg/L	6075	87	298	9874	37	419	16790

Table 2 Data of Flooded Oil By G03 Biogas Drive

Model NO.	Size, cm $\phi \times L$	Pore volume mL	Residual oil, mL	Fermented broth injected, mL	Pressure start/end MPa	Intresed of pre. %	Biogas Prodaced mL	Enhanced Oil recovery %
4	4×70	291	80	167	0.03/0.33	11.0	20	0.8
5	4×70	265	80	145	0.03/0.13	4.2	25	0.4
On average	-	278	80	156	0.03/0.23	7.1	22.5	0.6

Table 3 Injection of fermented broth into injection well

Injection Well NO.	69-1	69-2	69-7	69-11	69-13
Fermented broth, m^3	100	100	200	150	150

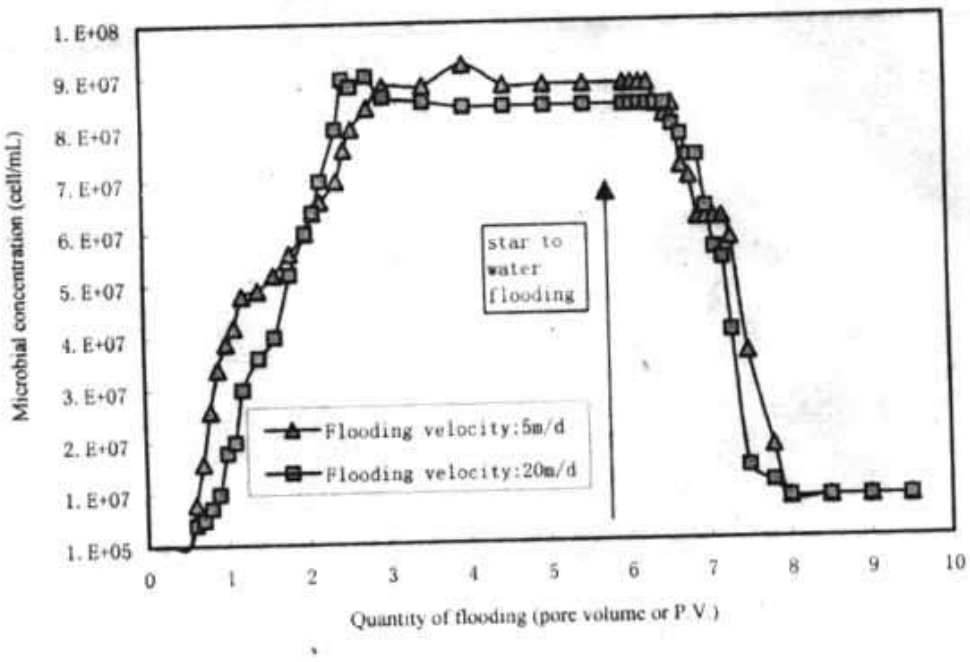


Fig. 2 Microorganisms migrated through pores of sandpack at two flooding velocities

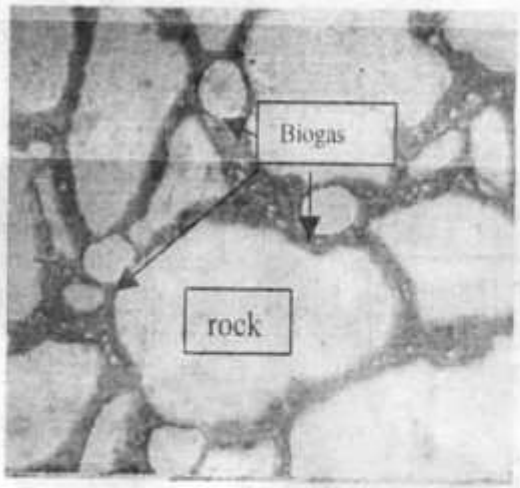


Fig9-1 Gases in pore produced by microbial action

Fig.9-2 "Jiamin effect" made by biogas

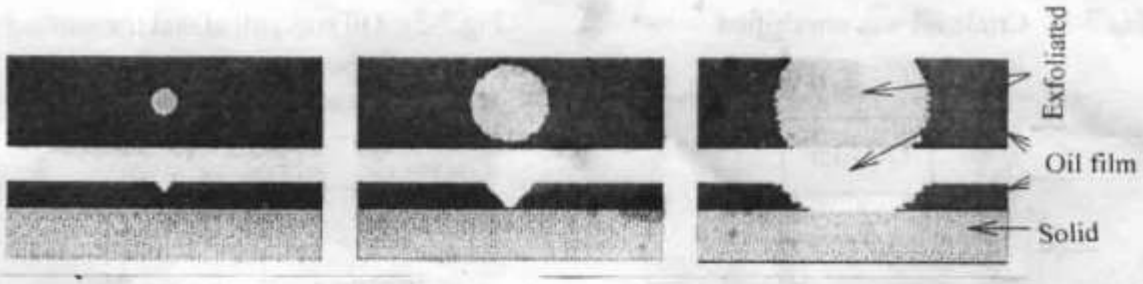


Fig. 10 Exfoliate oil film model simulated while single microorganism acting observing from up surface and from side

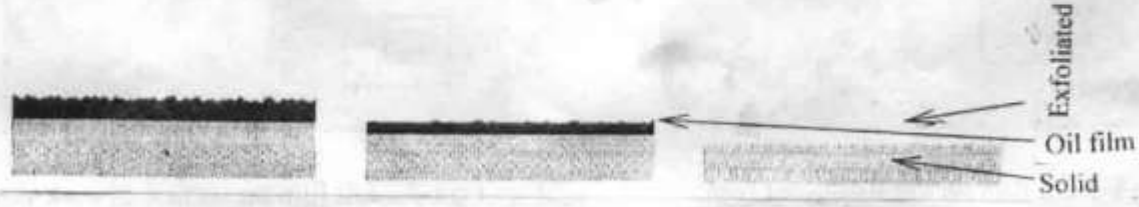


Fig. 11 Exfoliate oil film model simulated microbes observing from side