PRJ, Vol. 6 (January 1994); P. 9–17, 13 FIGS, 7 TABLES.

THE EFFECTS OF WAG PROCESS ON THE AREAL SWEEP EFFICIENCY

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تأثير تردد الماء والغاز (WAG) على مساحة الإزاحة الأفقية لطرق الحقن المتجانس

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تم استخدام طريقة الحقن المتجانس WAG لزيادة المردود النفطي في عدد من المكامن بالعالم وبنجاح. السبب الرئيسي لاستخدام هذه الطريقة هو زيادة المساحة الأفقية التي يمر من خلالها المزيج مما ينتج عن ذلك تحسين المردود النفطي.

في العادة تجرى التجارب المعملية لتحديد الحجم الأمثل للغاز والماء المراد حقنه حيث يتم المقارنة بين تردد الماء والغاز حسب النسب 1:1 1:2 2:1 لتحديد النسب المثلى.

الهدف الأساسي لهذا العمل هو بحث تأثير تردد الماء والغاز على مساحة الإزاحة الأفقية التي يمر من خلالها الغاز المزيح المستخدم في طرق الحقن المتجانس حيث تم إجراء تجارب معملية باستخدام مجسم يمثل مربع نموذج خماسي.

لقد تم تغيير حجم الماء والغاز بنسب 1:1 ,1:2 ,2:1 وتم أستنباط ثلاثة معادلات لتقدير مساحة الإزاحة الأفقية التي يغطيها السائل المزيح حسب الحركية للنظام (Mobility).

إن نتائج هذا العمل يمكن استخدامها في برامج طرق التحليل العددي والحسابي لتقدير كفاءة الحقن المتجانس.

ABSTRACT

Miscible flooding using an alternate solvent/water injection process (WAG) is currently being applied for enhanced oil recovery. The main reason of alternating solvent/water is to improve the mobility of the system which will yield better areal sweep efficiency and more reservoir oil contacted by the solvent.

Normally laboratory work is performed to assess or select the optimum WAG process of the miscible flooding system being investigated. The main objective of the laboratory work is to select the process (WAG 1:1, 1:2, or 2:1) which will result in an optimum displacement efficiency.

The purpose of this study is to investigate the effect of various WAG ratios on the areal sweep efficiency. An experimental work was conducted using one-quarter five spot model.

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The WAG ratio was varied for specified ratios of 1:1, 1:2, and 2:1. Three equations were obtained to predict the areal sweep as function of mobility ratio for various WAGs. The results of this work could be utilized in performing numerical and analytical miscible models for candidate EOR reservoirs.

INTRODUCTION

The search for future oil reserves has shifted the efforts of the oil industry to a new and more difficult areas for exploration, in addition to investigate the possibility of new technical means to produce the remaining oil after primary and secondary recovery. Currently various enhanced oil recovery methods are being investigated as possible new techniques for the enhancement of the world oil reserves.

Miscible solvent flooding is the selected EOR process by a number of Libyan oil companies. Volumetric sweep efficiency is the critical parameter effecting the performance of miscible process. Water-alternating solvent process has been proposed to improve the mobility of the miscible flooding system. This results in better sweep efficiency and more oil contacted by the solvent.

Many Authors have studied the five spot pattern because of its wide spread use in secondary and tertiary recovery operations. The effects of fluid mobility ratio on an areal sweep efficiency at breakthrough for an enclosed five-spot pattern has been studied by Ramey [1]. The system was also studied with an electrolytic tank by Check and Menzie [2] using fluid mapper models. Fay and Prats [3], Sheldon and Dougherty [4] employed analytical method, and Bredley, Heller and Odeh [5] using potentiometric models, sweep efficiency results is shown in Table 1. Habermann [6] studied the effects of miscible slug size, 10 to 25 percent hydrocarbon pore volume on oil recovery, keeping the mobility ratio constant. Habermann concluded that at high mobility ratios, a miscible slug of 10 percent hydrocarbon pore volume deteriorates after only a small fraction of the reservoir has been swept. Consequently the rich gas drive process approaches an ordinary gas drive. Mahaffey *et al.* [7] studied the effect of a slug on sweep efficiency utilizing a five spot pattern of a parallel-plate glass model. Mahaffey indicated that the presence of a slug, whose viscosity is intermediate between oil and solvent, increases the sweep efficiency of the oil-solvent system.

Lacy *et al.* [8] published areal sweep out results for a high pressure five-spot model where propane slugs were utilized to displace a methane saturated refined crude oil at 1550 psig. The propane slugs were driven by methane. He concluded that by using LPG slug process, a slug size of 5 percent or less is not effective in increasing oil recovery in horizontal reservoirs. Zekri and Natuh [9] have studied the effects of miscible WAG process on tertiary oil recovery. They concluded that WAG process had no significant effect on total oil recovery in water flooded sandstone-oil wet system. In their work the effect of areal sweep efficiency is not considered since composite model was employed in this study.

The size of the miscible slug could be determined experimentally or theoretically. Mahaffey calculated the optimum slug by setting the length of the mixing zone proportional to the square root of the distance traveled.

The purpose of this investigation is to provide some additional laboratory data that could help in determining the areal sweep efficiency of WAG process. The WAG ratios (1:1, 1:2, and 2:1) were tested in this work. The mobility of the system studied were: 0.456, 2.189, 20.65 and 45.206.

EXPERIMENTAL PROCEDURE

To achieve reproducibility of the results, it is essential that the basic properties of the model do not change from one experiment to the other. This objective was accomplished by using glass beads model. A model representing one-quarter of a five-spot was used in this investigation. A homogenous system was utilized in all runs. This was accomplished by fixing the mesh number of the glass beads (mesh no. 10). In this model of miscible displacement, molecular diffusion predominates is controlled by using the parallel plate spacing. The space between the plates was kept constant at 1.2 cm, which results in reducing convective mixing to arbitrary small levels.

The model total area was 412 square centimeters. The distance between injection point and producing point was 28 centimeters. Two types of mineral oil were utilized in this work, with viscosity 52.2 cp for oil A and 25.3 cp for oil B. The specifications of oil A and B is shown in Tables 2 and 3.

Table 1. Effect of Mobility Ratio on Areal Sweep Efficiency at Breakthrough Enclosed Five-Spot Well Pattern (Taken from Reference 5)

Areal Sweep Efficiency—Per cent					
Mobility Ratio *M*	Potentiometric Analyzer		Fluid Mapper[9]	X-Ray Shadowgraph[10,11]	Analytical Calculation
	Conductive Cloth-Uskon	Electrolytic Tank[6]			
infinite	62.6[14]	62.5			
10		64.5	52.7	51.0	
4	66.4	65.8	62.0	54.0	45.0[3]
2	68.8	68.0	68.0	60.4	
1	71.6	70.0	71.7	69.8	71.5
0.25	82.2	88.5	78.0	87.0	
0.1		94.5	82.0	100.0	

Table 2. The Specifications of Oil (A)

Specifig GRAVITY @ 60°F	0.885
API	28.3
Saybolt Viscosity @ 100 °F	350
Viscosity, cp @ 20°C	52.2
Pour Point, °F	-10
Flash Point, °F	430
Fire Point, °F	490
Distillation End Point, °F	952

Table 3. The Specifications of Oil (B)

Specifig GRAVITY @ 60°F	0.840
API	36.95
Saybolt Viscosity @ 100 °F	70
Viscosity, cp @ 20°C	25.3
Pour Point, °F	+15
Flash Point, °F	345
Fire Point, °F	420
Distillation End Point, °F	844

In this work, displacement with colored fluids were carried out as function of viscosity ratio. Production history was obtained by tracing the specified colored area. The experiment passed through a square cross section lucite tube placed at the production point of the system. Light source was placed under the model to assist in determining the percentage of displaced (clear) and displacing (colored) areas of the model. The data obtained with injection at one corner of the well and production at the other represents a symmetry element of one quarter of a completely developed five spot pattern (Fig. 1).

The laboratory work consisted of 12 flood experiments performed at constant temperature of 20°C. The flood procedures is discussed in the following:

- The model was cleaned and packed completely with glass beads.
- The model was saturated with the specific oil (displaced fluid) and total pore space was estimated, based on the mount of fluid injected in the model. Constant gravity force was applied in the fluid injection process.
- Total pore volume of fluid injection was kept constant for all runs at 20% of the pore volume.
- For WAG process of (1:1), 5% pore volume of water was injected and the process was repeated for four cycles.

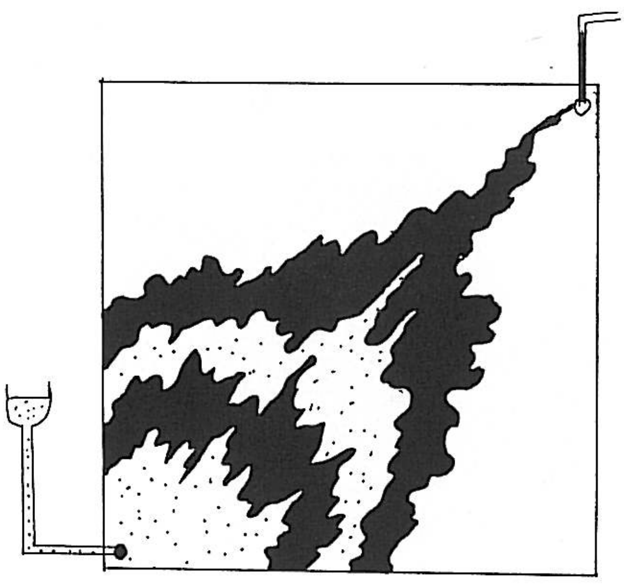

FIG. 1. Schematic diagram of the apparatus.

- WAG process of (1:2), 10% pore volume of solvent was injected and followed by 5% pore volume of water.
- WAG process of (2:1), 2.5% pore volume of solvent was injected followed by 2.5 pore volume of water.
- Upon completion of 20% pore volume of solvent injection, flow pattern of different stages were traced on transparency paper.

DISCUSSION

The results obtained in this study are, first, analyzed for the various WAG ratios at constant mobility ratio of 2.189. The total pore volume of the model is 200 cc, for WAG ratio 1:1 the total invaded (contacted area) is found to be 300 cm^2. While the total area contacted for WAG ratio of 1:2 is 322 cm^2 and 156 cm^2 for WAG ratio 2:1. The areal sweep efficiencies obtained for mobility ratio of 2.189 were 0.75, 0.85 and 0.39 for WAG ratios 1:1, 1:2, 2:1 respectively. These results indicate that WAG ratio 1:2 is the optimal value. Figs. 2, 3, and 4 show that the contacted area by the solvent is 316 cm^2 for 1:1 WAG, 322 cm^2 for 1:2 WAG and 162 cm^2 for 2:1 WAG.

The areal sweep efficiency of the various mobilities for the different WAGs are shown in Figs. 5, 6 and 7. The results of the system having a mobility of 0.456 indicate that a WAG ratio of 1:2 produces favorable sweep efficiency. Analyzing the results of performing

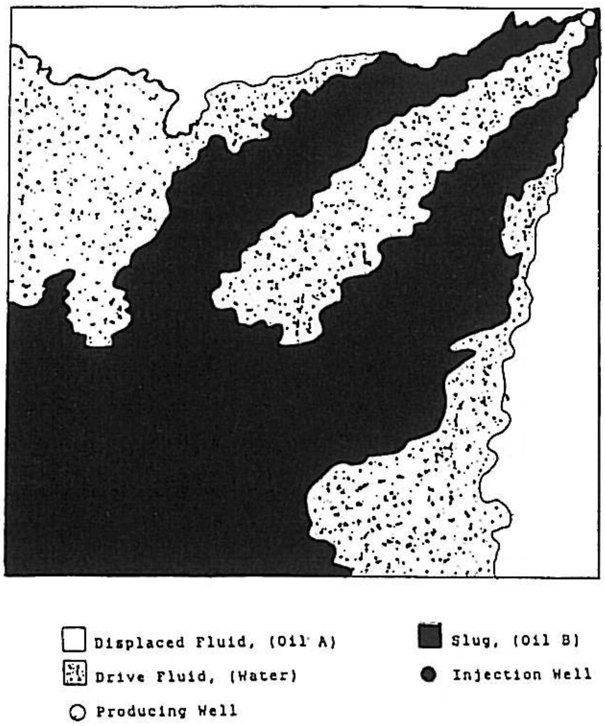

FIG. 2. Areal sweep of WAG 1:1 at mobility ratio 2.189.

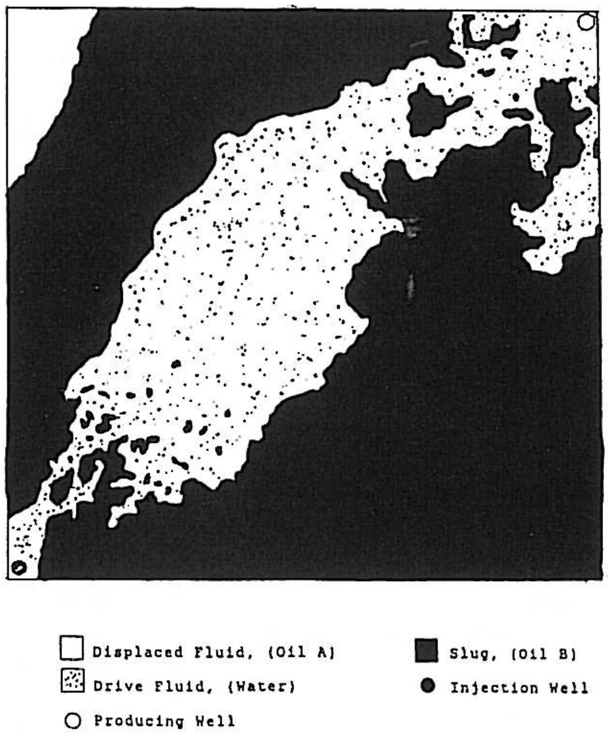

FIG. 3. Areal sweep of WAG 1:2 at mobility ratio 2.189.

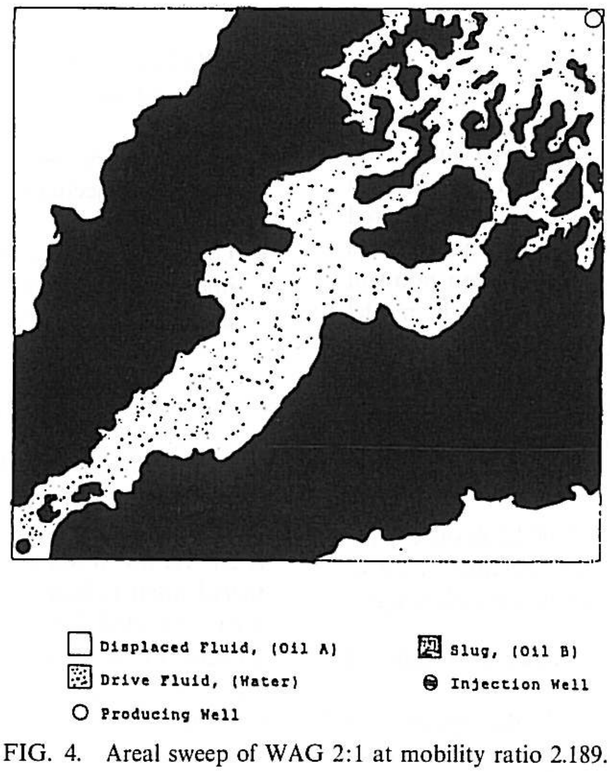

FIG. 4. Areal sweep of WAG 2:1 at mobility ratio 2.189.

the flood at a mobility of 45.206 for various WAGs 1:1, 1:2 and 2:1 yield an areal sweep of 0.5, 0.62 and 0.25 which indicate that the optimum system is WAG ratio 1:2.

Figures 8, 9 and 10 show the areal sweep of 1:1, 1:2 and 2:1. Changing the flood mobility to 20.65 and conducting the work at various WAGs 1:1, 1:2 and 2:1, yield area invaded of 248, 280 and 120 cm^2 respectively. The resulting areal sweep were 0.62, 0.70 and 0.3 for WAGs 1:1, 1:2 and 2:1 respectively. Again the optimum system is a WAG ratio of 1:2 which gives two fold increase of sweep over 2:1.

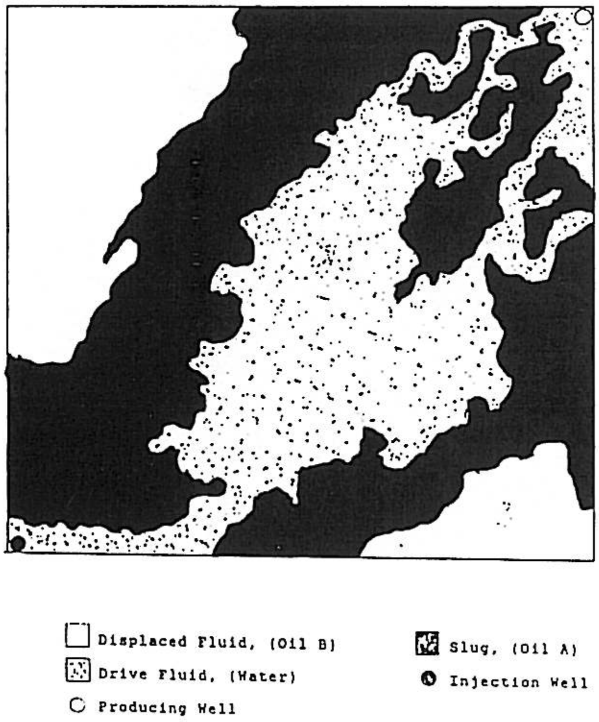

FIG. 5. Areal sweep of WAG 1:1 at mobility ratio 0.456.

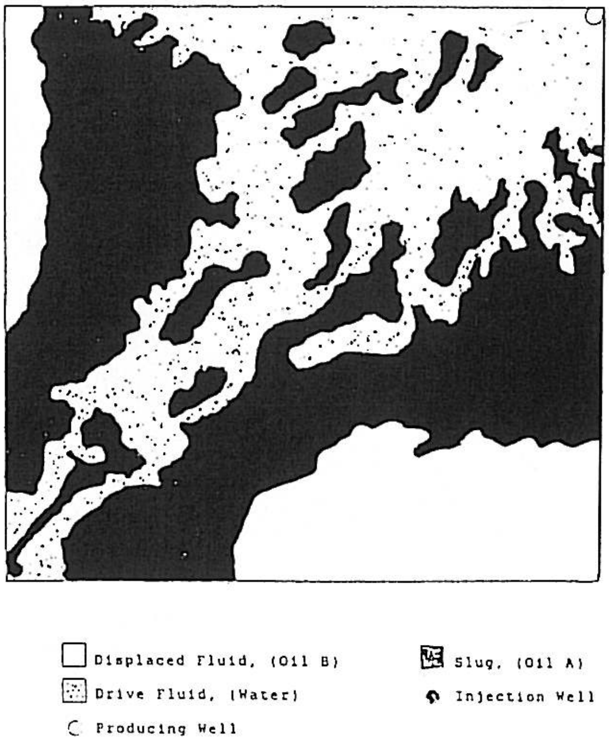

FIG. 6. Areal sweep of WAG 1:2 at mobility ratio 0.456.

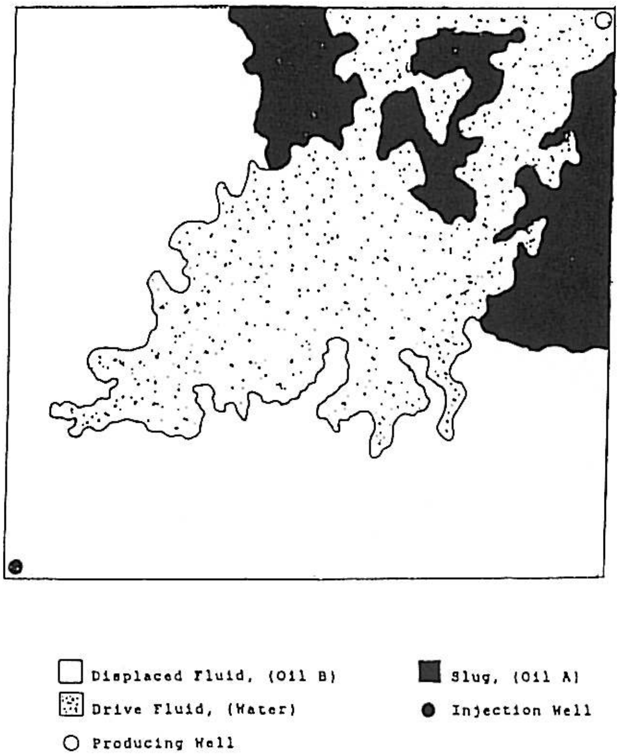

FIG. 7. Areal sweep of WAG 2:1 at mobility ratio 0.456.

Figures 11, 12 and 13 show the areal sweep of WAGs 1:1, 1:2 and 2:1. A WAG ratio of 1:1 yield areal sweep of 0.79 at mobility 0.456 and 0.5 sweep efficiency at mobility 45.206 which is around 58% increase, as presented in Tables 4, 5, 6 and 7.

Based on the results achieved in this study, the following equations are obtained:

WAG ratio of 1:1

$$\text{Areal sweep} = 0.825703 - 0.03538\log MR - 0.07765\log(MR)^2$$

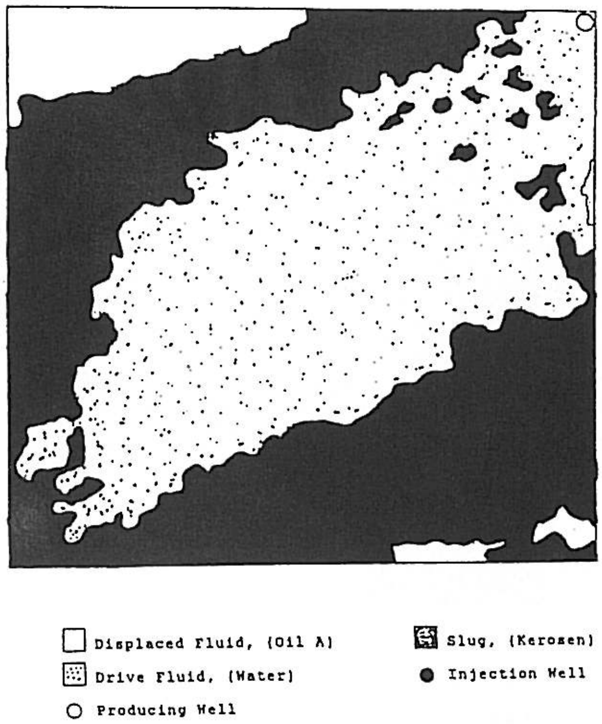

FIG. 8. Areal sweep of WAG 1:1 at mobility ratio 45.206.

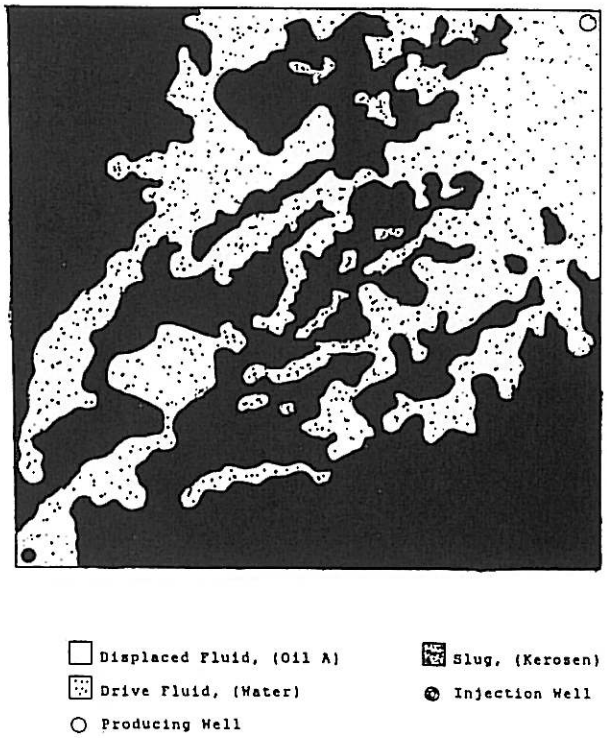

FIG. 9. Areal sweep of WAG 1:2 at mobility ratio 45.206.

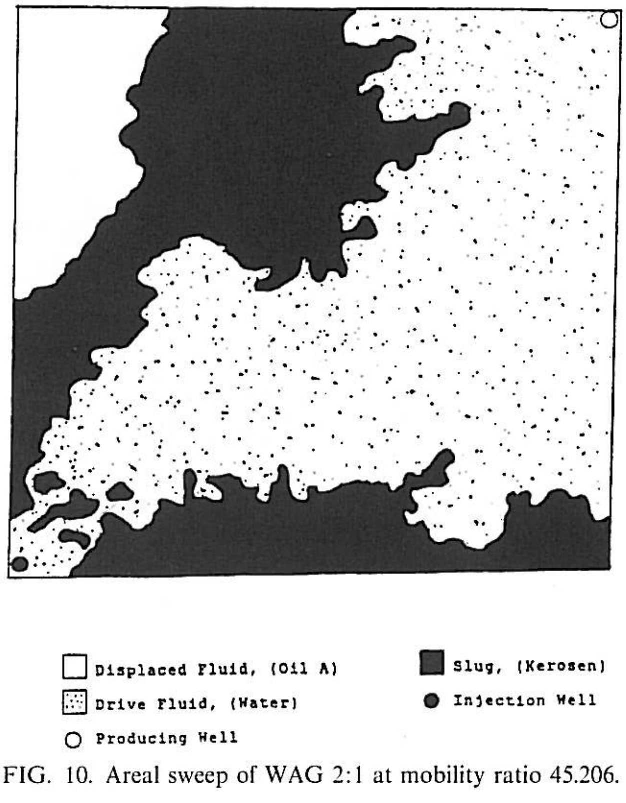

FIG. 10. Areal sweep of WAG 2:1 at mobility ratio 45.206.

WAG ratio of 1:2

$$\text{Areal sweep} = 0.825703 - 0.02636\log MR - 0.05734\log(MR)^2$$

WAG ratio of 2:1

$$\text{Areal sweep} = 0.402362 - 0.02223\log MR - 0.0422\log(MR)^2$$

The above equations could be utilized in reservoir simulation to estimate the areal sweep of the studied system.

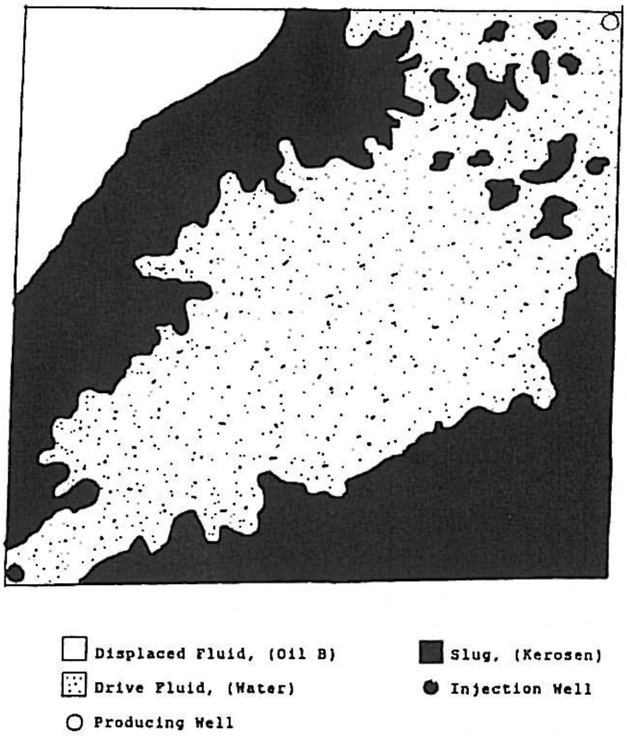

FIG. 11. Areal sweep of WAG 1:1 at mobility ratio 20.65.

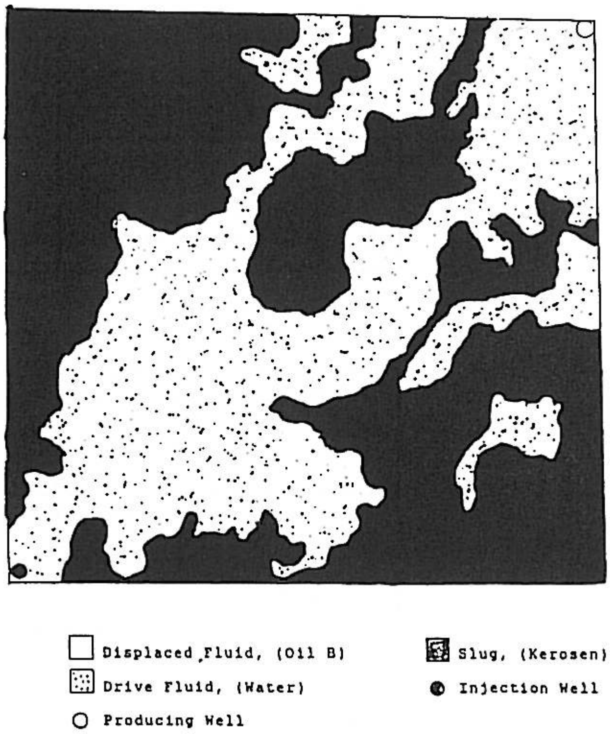

FIG. 12. Areal sweep of WAG 1:2 at mobility ratio 20.65.

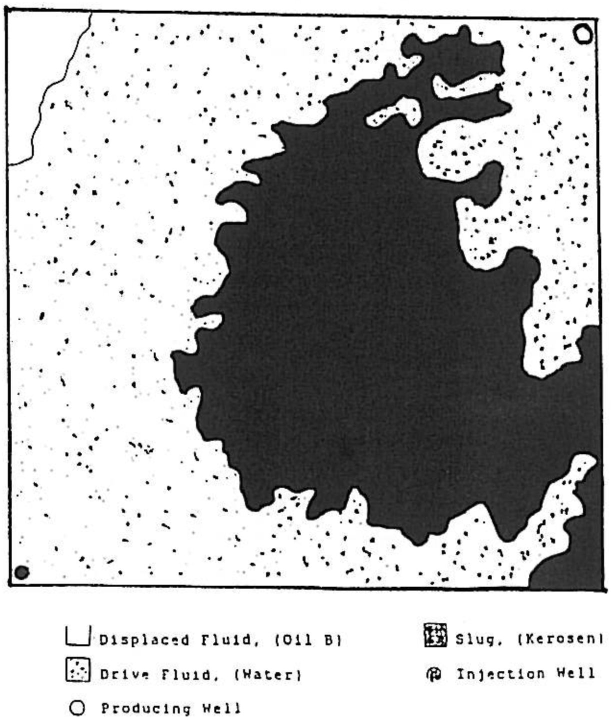

FIG. 13. Areal sweep of WAG 2:1 at mobility ratio 20.65.

Table 4. Areal Sweep of Different WAGs at Mobility Ratio 2.189

WAG	Displaced Fluid	Sulg	Drive Fluid	Total P.V. cc	Invaded Area cm^2	Area Sweep Efficiency
1:1	Oil (A)	Oil (B)	Water	200	300	0.750
1:2	Oil (A)	Oil (B)	Water	205	322	0.805
2:1	Oil (A)	Oil (B)	Water	200	156	0.390

Table 5. Areal Sweep of Different WAGs at Mobility Ratio 0.456

WAG	Displaced Fluid	Sulg	Drive Fluid	Total P.V. cc	Invaded Area cm^2	Area Sweep Efficiency
1:1	Oil (B)	Oil (A)	Water	205	316	0.790
1:2	Oil (B)	Oil (A)	Water	210	322	0.830
2:1	Oil (B)	Oil (A)	Water	205	162	0.405

Table 6. Areal Sweep of Different WAGs at Mobility Ratio 20.65

WAG	Displaced Fluid	Sulg	Drive Fluid	Total P.V. cc	Invaded Area cm^2	Area Sweep Efficiency
1:1	Oil (B)	Kerosen	Water	210	248	0.65
1:2	Oil (B)	Kerosen	Water	220	280	0.70
2:1	Oil (B)	Kerosen	Water	220	120	0.30

Table 7. Areal Sweep of Different WAGs at Mobility Ratio 45.206

WAG	Displaced Fluid	Sulg	Drive Fluid	Total P.V. cc	Invaded Area cm^2	Area Sweep Efficiency
1:1	Oil (A)	Kerosen	Water	200	200	0.50
1:2	Oil (A)	Kerosen	Water	215	248	0.62
2:1	Oil (A)	Kerosen	Water	200	100	0.25

CONCLUSIONS

- The model studied gives an insight into the effects of WAG process on the areal sweep efficiency. The most efficient WAG ratio for the studied system is found to be WAG of 1:2.
- Equations were developed to predict the areal sweep as function of mobility for WAGs of 1:1, 1:2 and 2:1. The results of this work could be utilized in analytical and numerical models to estimate the areal sweep efficiency of WAG process of 1:1, 1:2 and 2:1.

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REFERENCES

[1] Armofsky D.W., and Ramey, H.J., 1956, Trans. AIME 207, 205.
[2] Cheak, R.E., and Menzie, D.E., 1951, Tran. AIME 204, p205 (1955).
[3] Fay, C.H., and Parts, M., proc. Word Pctr. Congress, Sec II.
[4] Sheldon, J.W., and Doughherty, E.L., Oct. 8–11, 1961., Paper no. SPE 183, AIME Dallas mtg.
[5] Bradley, H.B., Heller, J.P., and Odeh, A.S., Oct. 2–5, 1960, paper no. 1585-G, AIME Denever mtg.
[6] Hebermann, B., 1960, 'Efficiency of miscible displacement as a function of mobility ratio', Trans., AIME 219, p. 264.
[7] Mahaffey, A.L., and Rulherford, W.M., and Matthews, C.W., March 1966, 'Sweep efficiency by miscible displacement in five-spot' Soc. Pet. Eng. J. 73–80, Trans., AIME 237.
[8] Lacy, J.W., Faris, J.E., and Brinkmann, F.H., Aug. 1961, 'Effect of bank six on oil recovery of the high pressure gas drive LPG-Bank process' JPT 806–12.
[9] Zekri, A.Y., Nnatuh, A., May 18–20, 1992, 'Laboratory study of the affects of miscible WAG process on tertiary oil recovery', (ADSPE 201) presented at 1992 Abu Dhabi 5th Petroleum Conference and Exhibition.
[10] Blackwell, R.J., Rayne, J.R., and Terry, W.M., 1959, 'Factors Influencing the efficiency of miscible displacement' Trans. AIME, 216.