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Review of Raguba Oil Field Miscibility Project

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مراجعة مشروع الإمتزاجية لحقل الراقوبة النفطي

علي الخفاجي

أحد أهداف مشروع الإمتزاجية لحقل الراقوبة النفطي دراسة الحد الأدنى لتركيب الإمتزاجية باستخدام خلائط مشتقة من غاز البترول المسيل والغاز الجاف. هدف آخر يتمثل في تعيين الحد الأدنى لضغط الإمتزاجية لزيت المكمن مع غاز ثاني أكسيد الكربون.

تم إنجاز تحضير عينتين من زيت المكمن (بضغطي نقطة غليان 1800 و2030 رطل للبوصة المربعة مطلق) وتحاليل الضغط والحجم والحرارة واستناداً على بيانات الضغط والحجم والحرارة، وخلائط غاز البترول المسيل/الغاز الجاف، وخواص ثاني أكسيد الكربون تم ضبط (معايير) معادلة الحالة بصفة مبدئية لتتلائم مع بيانات الضغط والحجم والحرارة. وقد جرى إثرها تطبيق معادلة الحالة للتنبؤ بالحد الأدنى لتركيب الامتزاجية والحد الأدنى لضغط الإمتزاجية.

وتعد هذه النتائج ذات قيمة لتصميم اختبارات الأنبوبة الرفيعة. وتم تعيين الحد الأدنى لتركيب الإمتزاجية لمذيبات غاز البترول المسيل / الغاز الجاف المشتقة مع عينتي زيت المكمن المشار إليها فيما سبق، تجريبياً باستخدام تقنية الإزاحة بالأنبوبة الرفيعة. تم تطبيق هذه التقنية أيضاً لتعيين الحد الأدنى لضغط الامتزاجية لثاني أكسيد الكربون مع عينة زيت بضغط 2030، استخدمت علاقات مسترجعات الزيت التراكمية مقابل الحجم المسامي للغاز المحقون لإيجاد مسترجع الزيت عند إختراق ثاني أكسيد الكربون.

كما جرى القيام باختبارات الانتفاخ لعينتي زيت المكمن المذكورتين بإضافة خلائط من مذيبات غاز البترول المسيل / الغاز الجاف المشتقة عند الحد الأدنى لتركيب الامتزاجية لهما – 40% و35% غاز بترول مسيل، كما تم استخدام ثاني أكسيد الكربون بنقاوة 99.19% لانتفاخ زيت المكمن عند ضغط 2035.

Abstract: *Study of Minimum Miscibility Composition (MMC) using mixtures of synthesized Liquefied Petroleum Gas (LPG) and Dry Gas (DG) is one of the objectives for Raguba oil field miscibility project. The other essential objective is to determine the Minimum Miscibility Pressure (MMP) of the reservoir oil with CO_2. Preparation of two reservoir oil samples (bubble point pressures (P_b) =1800 psia and 2030 psia) and PVT analyses are accomplished. Based on the PVT data and the LPG/DG mixtures and CO_2 properties, Equation of State (EOS) parameters were preliminary tuned to match the PVT experimental data. Thereafter, the EOS was applied to predict both MMC and MMP. These findings are valuable to design slim tube and swelling experiments. Then, MMC of synthesized LPG/DG solvents with the above two reservoir oil samples was determined experimentally using slim-tube displacement technique. This technique was also applied to determine the CO_2 MMP with oil sample of P_b = 2030 psia. Cumulative oil*

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recoveries versus pore volume gas injected relations have been used to find out the respective oil recovery at the CO_2 breakthrough.

Swelling tests were also carried out on these reservoir oils (P_b =1800 psia and 2030 psia) by adding mixtures of synthesized LPG and DG solvents at their MMC - 40% LPG and 35% LPG respectively. Carbon dioxide (CO_2 -99.19% pure) was also used to swell the reservoir oil 2035.

INTRODUCTION

Investigation of miscibility for different solvents and gases with reservoir oil is one of the most important processes to enhance oil recovery. Literatures on theoretical studies[1,2,3,4,5], experimental laboratory investigations[6,7,8,9] and field applications[10,11] of miscibility are available. Miscibility is achieved at certain conditions of pressure and temperature depending on the composition of both the reservoir oil and the injected gases or solvents. There are generally two types of miscible processes, the first contact miscible (FCM), where solvent (LPG) mix directly with reservoir oil in all proportions and their mixtures always remain in a single phase. The second process is the multiple contact miscible (MCM) process (dynamic miscibility processes). In which, gases or solvents are not directly miscible with reservoir oil, but under appropriate conditions of pressure, temperature and oil-gas or oil-solvent compositions, *in-situ* miscibility could be achieved through repeated contacts of the injected material with reservoir oil. The MCM is of three kinds: the vaporising, the condensing and condensing / vaporising miscible processes.

Representative reservoir fluid samples are very essential to obtain an accurate physical and chemical reservoir fluid properties [12,13, 14,15]. Therefore, two reservoir oil samples were prepared by direct recombination of the separator oil and gas obtained from Raguba oil field well No. E40. The bubble point pressures (P_b) of these samples were1800 psia and 2030 psia respectively. Conventional PVT analysis of the recombined oils was described elsewhere [18].

Minimum Miscibility Composition (MMC) determination for synthesized LPG/DG solvents and/ or Minimum Miscibility Pressure (MMP) of carbon dioxide with the above oils are essential for the Raguba enhanced oil recovery project[16,17,20,21,22]. Peng-Robinson cubic equation of state (EOS) modeling was first applied to predict the MMC of LPG/DG solvents with these reservoir oil samples [18,19,] The MMP of carbon dioxide CO_2 -99.19% pure with reservoir oil sample P_b = 2030 psia was also predicted by the EOS[23].

Two types of miscibility tests were conducted on reservoir oil samples of the Raguba oil field using slim tube displacement technique [21, 22]. First series tests were devoted for Minimum Miscibility Composition determination for the two reservoir oils. Each oil was displaced repeatedly at a pressure slightly higher than its bubble point pressure by solvents composite of different mole percentage of LPG and DG. The MMC of LPG/DG mixtures with oils having (P_b= 1800 psia and 2030 psia) was found to be equal to 40% LPG and 35% LPG respectively. The oil recovery mechanism for both oils was a condensing drive. Second series tests were conducted to determine the MMP, where the oil of (P_b =2030 psia) was displaced at different pressures using CO_2. The CO_2 MMP with this oil was found equal to 2710 psia. The mechanism of oil recovery was a vaporization drive.

Another objective of the Raguba EOR project is to conduct two types of swelling experiments [21,24,]. Firstly, to swell the two oils with the LPG/DG solvent at their MMC and secondly, to swell the reservoir oil of P_b = 2035 psia with CO_2. The swelling tests were carried out in five steps for the LPG/DG solvent and four steps for CO_2. In each step a specific volume of LPG/DG solvent and/or CO_2 was added to the respective oil in a long window PVT cell at a pressure of 5015 psia. At this high pressure, the solvent and/ or the CO_2 was forced to dissolve into the oil and form a new mixture. As a result, the composition and the physical properties of the new mixture will completely differ from the original one. Hence, bubble point pressure, swelling factor, mixture density, and gas oil ratio (GOR) were calculated at each solvent addition.

RESERVOIR OIL SAMPLE PREPARATION

Separator oil and gas were studied and directly recombined in the PVT cell at the current average GOR of 427SCF/STB to obtain a reservoir oil sample of bubble point pressure of 1800 psia at reservoir temperature of 206°F. This procedure was repeated at GOR of 480 SCF/STB to obtain an oil sample of bubble point pressure equal to 2030 psia. A Core LAB long window PVT cell with a heating jacket was used for preparing and testing of the reservoir oil samples.

Complete PVT analyses were carried out on each of the above reservoir oils.

TUNING OF EOS PARAMETERS

In order to assure the accuracy of EOS predictions of miscibility conditions for these oils (P_b = 1800 and P_b = 2035 psia), the EOS parameters must first be tuned to match experimental data. Then more reliable analyses of recovery mechanism and miscibility conditions may be made. Before tuning commencement, C_7/fraction for both oils should be characterized. It was found that two pseudo components of C7+ were adequate to model these oils. The properties of the two pseudo components of C_7+ are: (MW of C_7-C_{13} and C_{14}+) 139 and 302 g/g-mole respectively, Pc= 23.72 and 14.84 Atmosphere and Tc = 707 and 956°K, respectively. Then, tuning of EOS is accomplished using regression option in CMG PROP software. The regression variables are critical pressure and temperature, the volume shifts of methane, hexane and the C_7+ components. Also, the binary interaction coefficient exponent and the molecular weights of the C_7+ components were used as regression variables. These variables were adjusted to match the experimental data for both oils including the bubble point pressures, the constant mass expansion data, the differential liberation data, and the separator flash data. A high weight was given for matching the bubble point pressure data, since matching other experimental data/ depends on having an accurate bubble point pressure. After several different regression runs, a good match with the experimental data was achieved (See figures. 1-6 as an example for oil P_b=1800 psia).

DETERMINATION OF MICIBLLITY CONDITIONS USING EOS

Using the tuned EOS parameters, miscibility conditions and the mechanism of oil recovery can be analysed using pseudo-ternary diagrams as well as pressure-composition and pressure-temperature diagrams. First, the pressure-temperature diagram was generated for each oil (Fig. 7). These diagrams are consistent with the typical diagrams for black oils with the reservoir temperature much lower than the critical temperature. Also, pressure-temperature diagrams for LPG/DG solvents are generated. It appears that these solvents are of a single phase at the injection conditions (1850 psia and 2100 psia and reservoir temperature = 206 °F) as revealed in figure 12. Next, series of pseudo-ternary diagrams were generated for oil P_b =1800 at injection pressure of 1850 psia contacted by various solvents made up by blending LPG with dry gas in different molar ratios (from 30% to 60% LPG). The compositions of these various solvents, LPG and DG are presented in Table 1. Figure 8 shows the ternary diagram for this oil contacted by solvent of *55%* LPG. From this diagram, evidently miscibility is achieved when the solvent composition is around 55% LPG or greater. The pressure-composition diagrams with different solvents are shown (Fig. 9) From this figure, it is evident that until the LPG/DG ratio is *50%* the principal mechanism of recovery will be via vaporising mechanism. However, at higher LPG/DG ratios, the mechanism becomes principally a condensing mechanism. Thus, miscibility is achieved with LPG solvent of 55 % or greater by a multiple-contact conde6sing mechanism, where the liquid phase becomes enriched with intermediate compounds (C_2-

Table 1. Solvents composition of the blended LPG/DG samples used in slim tube experiments.

Comp.	Dry Gas	0.15* LPG	0.20 LPG	0.25 LPG	0.30 LPG	0.35 LPG	0.40 LPG	0.45 LPG	0.55 LPG	LPG
	Mole%	Mole %	Mole %	Mole %	Mole %	Mole %	Mole %	Mole %	Mole %	Mole %
N_2	1.35	1.15	1.08	1.02	0.95	0.88	0.82	0.75	0.61	
C_1	86.42	73.46	69.14	64.81	60.49	56.17	51.85	47.53	38.89	
C_2	8.35	7.47	7.18	6.88	6.59	6.29	6.00	5.71	5.12	2.47
C_3	2.83	6.85	8.20	9.54	10.88	12.22	13.56	14.90	17.58	29.65
IC_4	0.39	3.79	4.92	6.05	7.18	8.31	9.44	10.57	12.84	23.03
IC_4	0.65	7.28	9.49	11.70	13.91	16.12	18.33	20.54	24.96	44.85

*Mixture of solvent contains 15% LPG + 85% DG

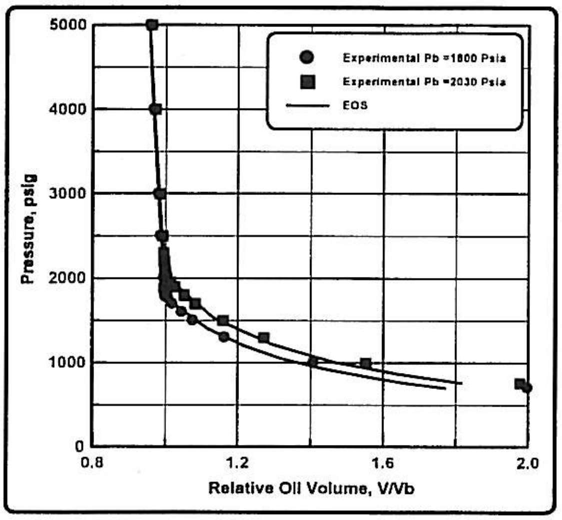

Fig. 1 EOS match, relative oil volume *vs* pressure, P_b = 1800 and 2030 psia, Raguba oil field, well No. E40.

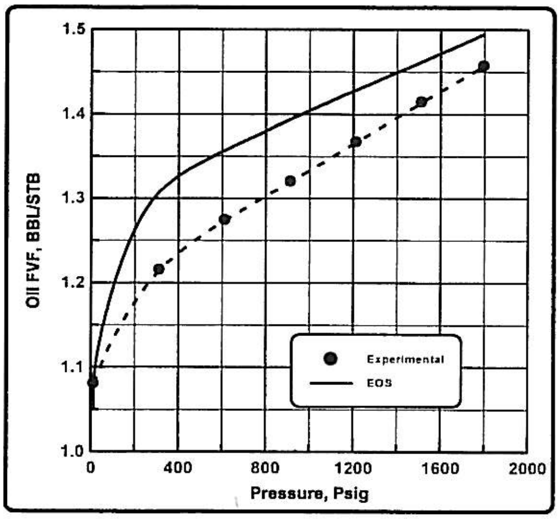

Fig. 2. EOS match, oil FVF *vs* Pressure, P_b = 1800 psia, Raguba oil field, well No. E40.

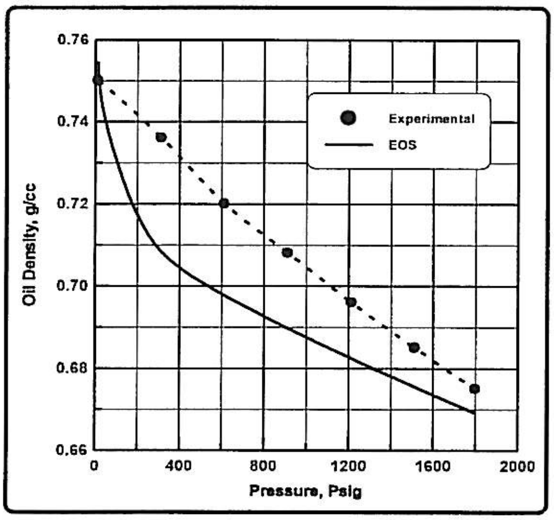

Fig. 3. EOS match, oil density *vs* pressure, P_b = 1800 psia, Raguba oil field, well No. E40.

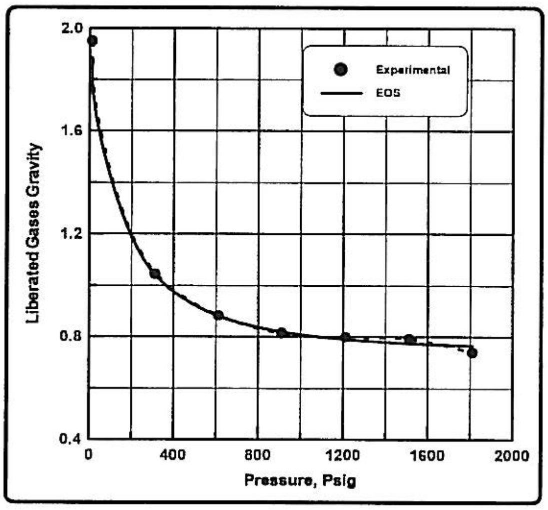

Fig. 4. EOS match, liberated gases gravity *vs* pressure, P_b = 2030 psia, Raguba oil field, well No. E40.

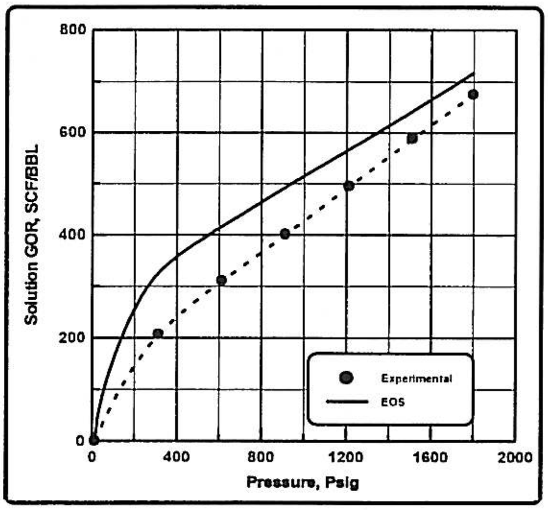

Fig. 5. EOS match, solution GOR *vs* pressure, P_b = 1800 psia, Raguba oil field, well No. E40.

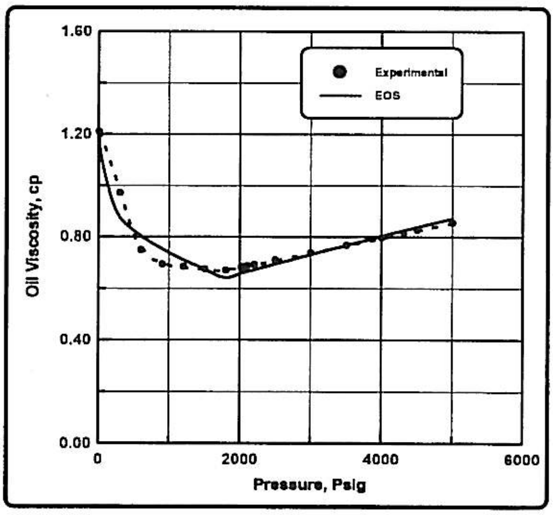

Fig. 6. EOS match, oil viscosity *vs* pressure, P_b = 1800 psia, Raguba oil field, well No. E40.

C_6) to the point that it becomes miscible with the injected solvent.

In the same manner, the MMC of LPG/DG solvent with oil P_b=2030 psia at pressure of 2100 psia found to be equal to 50 % and greater as shown in figure 10. Also, it appears that up to 40% LPG in the solvent, the principal mechanism of recovery is a multiple vaporizing mechanism but for more LPG in the solvent the mechanism becomes primarily a multiple condensing mechanism.

Ternary diagrams[16,17] for oil P_b =1800 psia contacted with CO_2 at several different pressures were generated to determine the miscibility pressure for this oil with CO_2. The ternary diagram for pressures of 1850, 3000, and 4400 psia is shown (Fig. 11). For all these pressures no miscibility was achieved at pressure less than 4400 psia and the mechanism of recovery seemed to be a condensing/vaporising mechanism. However, the results do not seem correct because CO_2 should be able to achieve miscibility with most black oils at pressures lower than 3000 psia. Therefore, the MMP of CO_2 with this oil was calculated using Glaso[20] correlation for pure CO_2 and found to be equal 2572 psia. Similar results were achieved for oil P_b2030 contacted with CO_2 at several different pressures, 2100, 3000 and 4400 psia. Also, the MMP of CO_2 with this oil was calculated using Glaso[20] correlation for pure CO_2 and found=2669 psia. Accordingly, the results obtained by EOS may be misleading because the EOS was tuned only with black-oil data and not data for oil mixed with CO_2 that is not available yet.

EXPERIMENTAL WORK

Synthesizing of LPG and Dry Gas

Sirte Oil Company (SOC) has specified the composition of two basic mixtures, a Dry Gas (DG) mixture and Liquefied Petroleum Gas (LPG) mixture as shown in Table 1. The two basic mixtures have to be synthesized from pure hydrocarbon components. Addition of individual component was carried out using synthesis of gas mixtures, *e.g.*, compounds like methane, ethane, etc. in the required proportion in one container. This can be done either by volumetric, or by gravimetric method. The gravimetric method was preferred because of the relatively small masses of gas components, which had to be combined. Accordingly, both mixtures were synthesized by weight compositional balance. Therefore, a precision weight transducer (Type Z6H) and an electronic readout (Type Hottinger Baldwin DK38 digital) was used. Sufficient amounts of LPG and DG mixtures needed for all slim tube experiments were prepared following this method.

LPG/DG Solvent Preparation

Sufficient amounts of solvents made up by blending LPG with DG in molar ratios of LPG/DG: 55/45, 45/55, 35/65, 25/75 and *15/85* were prepared and used in the slim tube displacement tests for the reservoir oil of P_b=1800 psia. Also, solvents with mole percents of LPG/DG: 40/60, 35/65, 30/70, 20/80 and 15/85 were prepared and used to displace the reservoir oil of P_b2030 psia.

Determination of MMC And MMP Experimentally

The slim tube technique for oil displacement has been used as the dynamic means of miscibility [2,3,8,10]. Miscibility apparatus was used for oil displacement by either mixtures of LPG/DG solvent to find the MMC or CO_2 to find the MMP.

Miscibility apparatus

The CORLAB Inc. miscibility apparatus was used in this investigation (Fig. 13) It consists of a pressure control system to monitor the inlet and the outlet pressures of the slim tube, a temperature control system includes an air bath and has a control panel to yield a constant temperature, a fluid flow control system comprising of a motorized mercury pump has a minimum rate in the range of 6-9 cm^3/h, a density meter to measure the produced fluid density at reservoir temperature and test displacement pressure. It is also connected to a fluid separator at which the recovered hydrocarbon and liberated gas were separated at atmospheric conditions. A coiled slim tube (stainless steel) with 40 ft long and 0.18 in. ID packed with 80/120 mesh Ottawa sands was used. Porosity and permeability of the slim tube column are 40.5% and 9.56 Darcys respectively.

Slim tube displacement test

The slim tube system and the solvent cylinder were cleaned, dried and evacuated. The required solvent volume was injected into the solvent cylinder and pressurized using the Ruska motorized pump. The

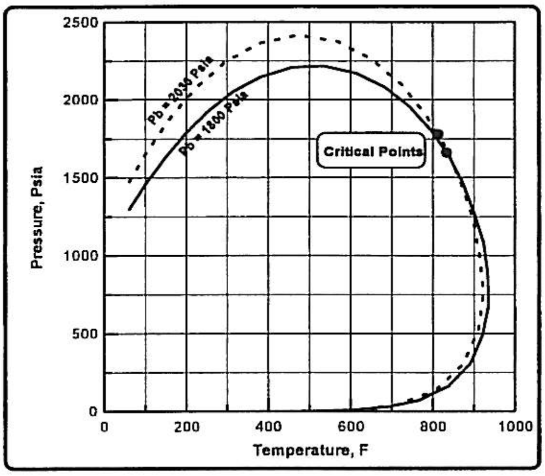

Fig. 7. EOS generated, pressure – temperature diagram, P_b = 1800 and 2030 psia, Raguba oil field, well No. E40.

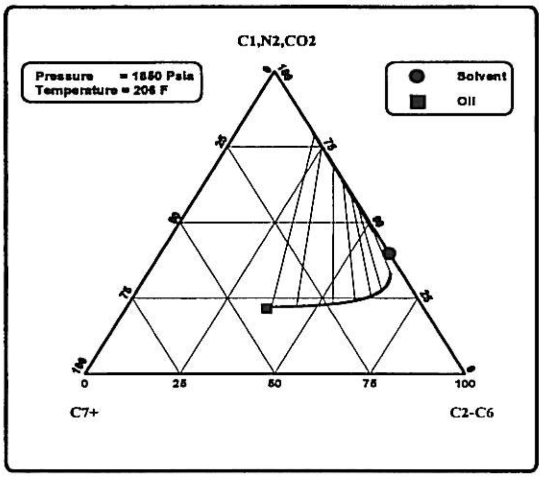

Fig. 8. Ternary diagram for solvent LPG/dry gas ratio 55/45, reservoir oil of P_b = 1800 psia at 206 °F.

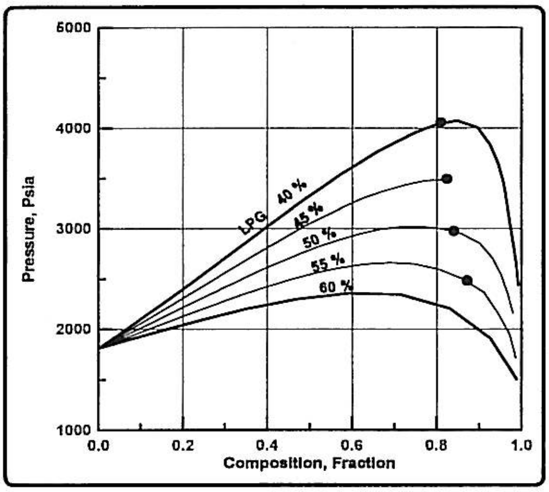

Fig. 9. EOS generated, pressure – composition diagram for oil 1800R and 5 mixture of LPG and dry gas, Raguba oil field, well No. E40.

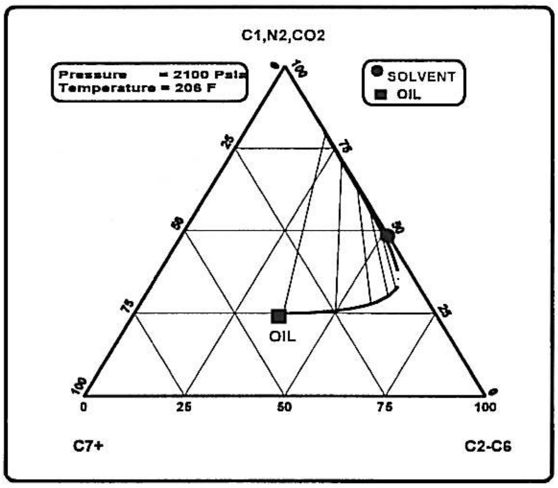

Fig. 10. Ternary diagram for solvent LPG/DG ratio 50/50 reservoir oil of P_b = 2030 psia at 206 °F, Raguba oil field, well No. E40.

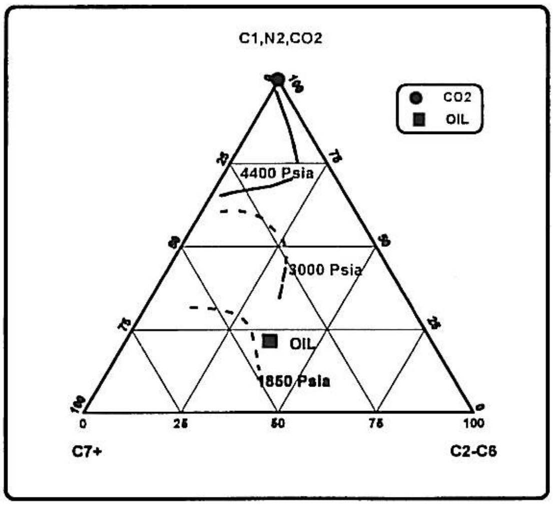

Fig. 11. Ternary diagram for Co_2 and reservoir oil of P_b = 1800 psia at 206 °F, Raguba oil field, well No. E40.

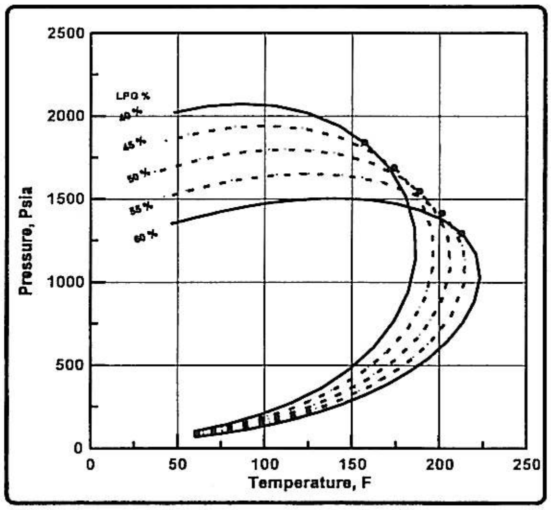

Fig. 12. EOS generated, pressure – temperature diagram for different mixture of LPG and DG, Raguba oil field, well No. E40.

slim tube and the downstream part of the system were filled first with toluene at pressure equal to the injection pressure. Then, a volume of the reservoir oil about 1.2-1.5 of the system volume was injected to displace the toluene. A slim tube displacement test was started after heating and stabilizing the reservoir temperature at 206°F.

A-Solvent injection

The solvent in the solvent cylinder was injected into the slim tube by a motorized pump to displace the reservoir oil at the required injection pressure and at constant flow rate. The produced gas and oil were sampled at regular intervals of 60 minutes.

B-Blow down

When solvent volume of about 1-1.2 of the system volume was injected, the inlet valve of slim tube was closed and the blow down was started. The downstream pressure was slowly lowered at the backpressure regulator to the atmospheric pressure and the recovered oil weight and gas volume were measured.

C-Toluene wash

At the end of the blow down, a sufficient amount of toluene was injected into the slim tube and the recovered oil and toluene was collected in a flask pre weighted. The flask and the contained fluids were weighted. Toluene in the flask was evaporated using Buchi Rotavapor type RE- 121 and the flask was re-weighed. Then the weight of the remaining oil in the flask was calculated.

Swelling Experiments

LPG/DG solvent preparation

Based on the slim tube experiments, the minimum miscibility compositions of LPG/DG needed for oil samples of P_b=1800 psia and 2035 psia were found 40/60 and *35/65* molar ratios respectively. Therefore, sufficient solvent volumes were prepared by blending LPG and DG at the nominated molar ratios. Compositions of these mixtures were determined by chromatography and listed as shown in Table 2. The composition of both reservoir oils was also presented in Table 2.

Swelling tests

Three swelling experiments were carried out to investigate the effect of LPG/DG solvent mixture and/or CO_2 injection into the reservoir oils of bubble point pressure of 1800 psia and 2035 psia. A (COREXPORT) long window PVT cell apparatus was used for the oil swelling experiments. Volumes of LPG/DG solvent mixtures of a molar ratio of 40/60 were calculated at solvent: oil molar ratios of 15, 30, 50, 70, and 85 percents and were added to the oil sample of bubble point pressure of 1800 psia in a PVT cell in five steps. This procedure was replicated for the oil sample of bubble point pressure of 2035 psia using LPG/DG solvent of a molar ratio *35/65.* CO_2 was added into a new oil sample of bubble point pressure of 2035 psia in the PVT cell at CO_2 /oil molar ratios of *15,* 30, 50, and 70 percents in four steps following the same procedure.

In each addition of LPG/DG solvent or CO_2 into the corresponding oil, a constant composition expansion study was performed on the new mixture. All PVT data were smoothed using the dimensionless compressibility Y-Function method. Liquid and gas volumes at pressures below the bubble point pressure were calculated from the Cathometer reading taken at the gas-oil interface for the mixture in the PVT

Table 2. Compositional analysis of injection solvents in swelling tests, Raguba oil field, well No. E40.

Component	Solvent for oil P_b=1800 psia (40% LPG + 60% DG)	Solvent for oil P_b=2035 psia (35% LPG + 65% DG)
	Mole %	Mole %
N_2	1.49	1.70
CO_2	0.02	0.00
C_1	53.06	57.79
C_2	6.14	6.59
C_3	12.91	12.03
IC_4	8.93	7.46
NC_4	17.21	14.27
IC5	0.03	0.03
NC5	0.02	0.03
IC6	0.03	0.04
NC6	0.03	003
C7+	0.13	0.03
Total	100.00	100.00

cell. Swelling factor, mixture density, and gas oil ratio were also calculated at each solvent addition. Solvent: oil molar ratio was re-calculated based on the actual solvent moles added into the reservoir oil.

RESULTS AND DISCUSSIONS

LPG/DG Solvents MMC Determination with Oils of P_b =1800 and 2030 psia

From the preliminary tuning of the equation of state (EOS) carried out on the reservoir oil of P_b = 1800 psia[2,6] solvent MMC was predicted at *55/45* of LPG/DG mole percentage. The first slim tube displacement test was then started at the above predicted solvent composition. This run in turn shows that the reservoir oil was completely miscible with the displacing solvent at the test conditions (injection pressure is 1850 psia at reservoir temperature equal to 206°F).

Miscibility of LPG/DG mixture solvent with reservoir oil is defined in this investigation as: the composition of the solvent in which *95%* or more of the oil saturating the slim tube system is recovered when solvent volume of about 1.2 of the pore volume is injected. Accordingly, LPG/DG compositions of *55/45* and *45/55* molar ratio solvents were found miscible in displacing the reservoir oil since the cumulative oil recovery was higher than *95%*. The other three compositions, LPG/DG: *35/65, 25/75* and 15/85 molar ratio solvents were immiscible as shown in figure 14. LPG/DG solvent mixture of a molar ratio 40/60 was found as the MMC. This ratio was obtained from the intercept of the straight lines of the miscible and the immiscible regions as represented (Fig. 14). Obviously the EOS for this oil overestimated the minimum miscibility composition.

Another five slim tube displacement experiments were conducted on reservoir oil of P_b=2030 psia. Various solvents made up by blending LPG with DG in molar ratios (40/60, *35/65*, 30/70, 20/80 and 15/85) were used. Based on the preliminary tuning of the equation of state (EOS) curried out on this oil, the MMC was predicted at a solvent of *50/50* of LPG/DG mole percentage. Because the EOS was overestimated the MMC as indicated in reservoir oil of P_b=1800 psia, a molar ratio 40/60 was judged to start the slim tube displacement series tests. At this molar ratio, the solvent was completely miscible with the displaced oil. The injection pressure on these five series experiments was constant and equal to 2100 psia. The intercept of the two straight lines in figure 15 shows that a minimum miscibility composition of 35% LPG and 65% DG was required to achieve miscibility with reservoir oil P_b =2030 psia. Overestimating of the MMC by EOS for this oil was also verified.

Recovery mechanism for both oils was found to be a multiple contact condensing drive mechanism in which hydrocarbon intermediate compounds (C_2-C_6) in the solvent condense into the reservoir oil until a sufficient quantity of this solvent exists at the displacement front to cause miscibility with the oil. An oil recovery more than 100% was observed in the slim tube displacement tests when the solvent was miscible with the oil, probably because of the predominant condensing drive mechanism.

MMP Determination for Oil of P_b = 2030 psia

To fmd the minimum miscibility pressure (MIMP) of CO_2 (99.18% pure) with reservoir oil of bubble point pressure 2030 psia, five CO_2 injection pressures: 3515, 3015, *2515*, 2315 and 2115 psia were conducted for oil displacement in the same slim tube described before.

Cumulative oil recovery versus pore volume gas injected relations were used to find the respective oil recovery at the CO_2 breakthrough. Minimum miscibility pressure of CO_2 with reservoir oil is defined as the pressure at which 80% or more of oil saturating the slim tube system is recovered at CO_2 breakthrough. The MMP of CO_2 with this oil was predicted to be 2710 psia at reservoir temperature-206°F as illustrated in figure 16.

The mechanism of oil recovery was a vaporizing drive at which CO_2 vaporizes hydrocarbon compounds (C_2-C_{30}) from the reservoir oil until a sufficient quantity of these hydrocarbons exists at the displacement front to cause miscibility with the oil. Cumulative oil recovery was found to be less than 100% when the CO_2 was miscible, because of the predominant vaporizing drive mechanism. The MIMP of CO_2 with this oil was calculateusingG1aso[23] correlation for pure CO_2 and was found to be equal to 2667 psia, which is in good agreement with the experimental results.

SWELLING OF RESERVOIR OILS P_b =1800 PSIA AND P_b =2035 PSIA WITH LPG/DG SOLVENTS

On the basis of the slim tube displacement experiment, the 40% LPG plus 60% DG hydrocarbon solvent was found to be miscible with oil of P_b =

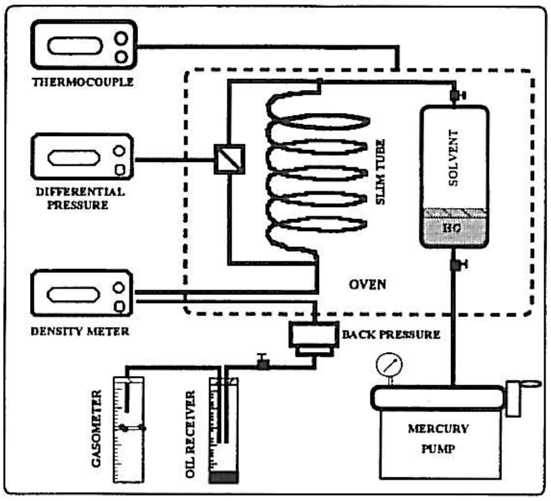

Fig. 13. Schematic diagram of slim tube apparatus.

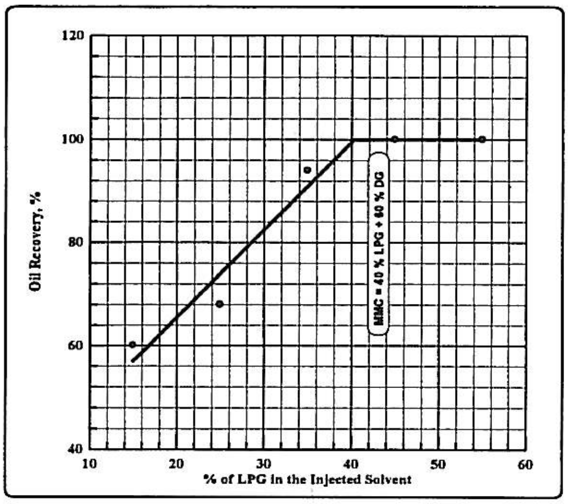

Fig. 14. Oil recovery as a function of % LPG in the injected solvent, reservoir oil (P_b 1800 psia), Raguba oil field, well No. E40.

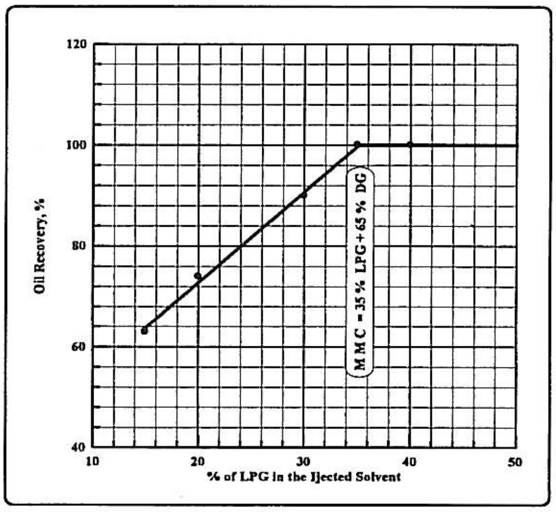

Fig. 15. Oil recovery *vs* pressure for reservoir oil (P_b 2030 psia) with CO_2, Raguba oil field, well No. E40.

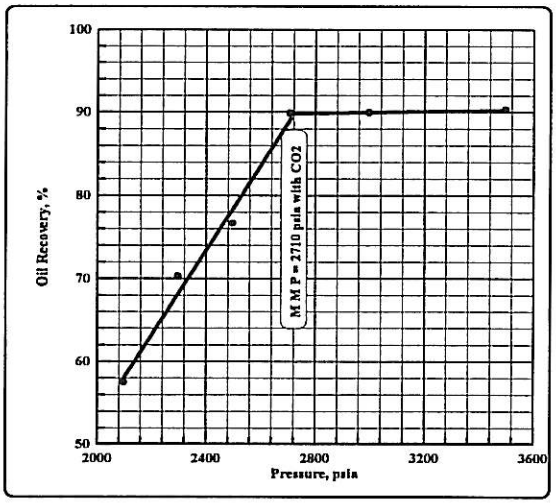

Fig. 16. Oil recovery *vs* pressure for reservoir oil (P_b 2030 psia) with CO_2, Raguba oil field, well No. E40.

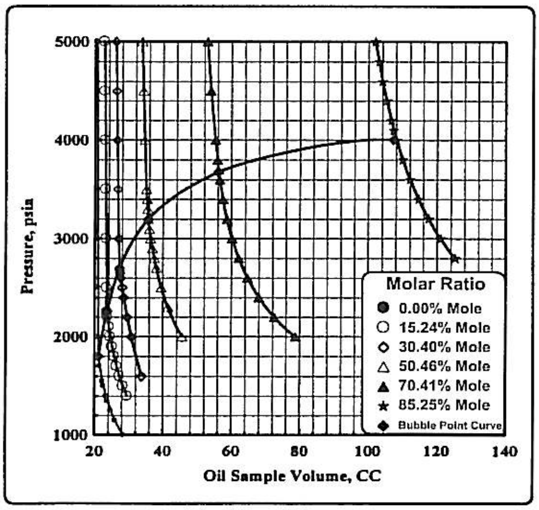

Fig. 17. Pressure – volume relations obtained from swelling of reservoir oil 1800R with 40% LPG +60% DG solvent at different LPG – oil molar ratio.

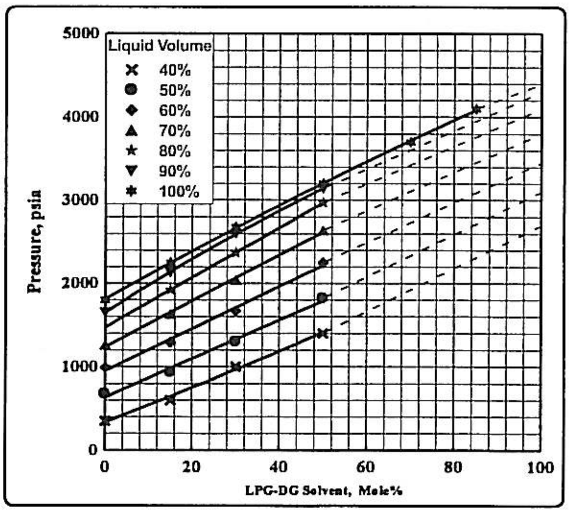

Fig. 18. Swelling test, quality lines, P_b = 1800 psia with 40% LPG +60% DG solvent at different LPG/DG – oil molar ratio.

1800 psia at reservoir temperature 206°F. Table 3 shows the summary of hydrocarbon swelling tests carried out on the reservoir oil sample of P_b =1800 psia.

The above oil was swelled by adding LPG/DG solvent mixture of a molar ratio 40/60 in five steps. Pre-calculated solvent volume for each addition was done according to solvent: oil molar percents of *15*, 30, *50*, 70, and 85 as shown in Table 3. Pressure versus oil sample volume is plotted in figure 17. Pressure-composition (P-X) diagram represents quality lines as liquid percents in the swollen oil are shown in figure 18. Swelling factor and mixture density at the bubble point were calculated and illustrated (Figs. 23 and 24) as a function of the solvent mole percent added to the oil sample.

Table 3. Summary of hydrocarbon swelling test at 206 °F for reservoir oil sampl of P_b = 180 psia, Raguba oil field, well no. E40 .

Fluid	LPG/DG mole %	Saturation pressure psia	Swelling factor	Mixture density g/cc
Resvoir oil	0.000	1800	1.000	0.6749
Mixture # 1	15.24	2263	1.115	0.6468
Mixture # 2	30.40	2702	1.288	0.6107
Mixture # 3	50.46	3195	1.682	0.5556
Mixure # 4	70.41	3676	2.652	0.4816
Mixture # 5	85.24	4006	5.072	0.4194

Peg-Robinson equation of state (EOS) is applied to model the swelling experimental data for oil of P_b = 1800 psia, using the Computer Modelling Group (CMG PROP) software. Table 4 presents a comparison of the experimental data with EOS predicted values for saturation pressure and swelling factor for oil sample of P_b =1800 psia. Swelling factor values predicted by EOS match very well with the data experimentally obtained for five additions of LPG/DG mixtures as represented in figure 23. Predicted saturation pressures using EOS modelling are in a good match with the experimental data when LFG/DG mole is 50% and lower. At a higher molar percent, the predicted saturation pressures are under estimated.

LPG/DG solvent mixture of a molar ratio 35/65 was found as the minimum miscibility composition (MMC) with oil P_b = 2035 psia at reservoir injection conditions (2100 psia and 206°F). The compositional analysis of the reservoir oil and the injected hydrocarbon solvent *(35% LPG+65% DG)* were listed in Table 2. Therefore, this solvent was applied to swell reservoir oil at five steps. LPG/DG solvent mixture at solvent: oil mole percentages of 15, 30, 50, 70 and 85 were used. Table 5 shows the summary of hydrocarbon swelling tests carried out on the reservoir oil sample of P_b =2035 psia. Pressure versus oil sample volumes were plotted (Fig. 19). Pressure-composition (P-X) diagram represents quality lines as liquid percents in the swollen oil were shown (Fig. 20). Swelling factor and mixture oil density obtained from these tests as a function of the solvent/mole percent are plotted (Figs. 23 and 24).

SWELLING OF RESERVOIR OIL P_b = 2035 PSIA WITH CO_2

Carbon dioxide CO_2 (99.19% purity) was applied to swell the reservoir oil of bubble point pressure 2035 psia at reservoir temperature of 206 °F. Volume of CO_2 added to the reservob-oil was calculated at the CO_2: oil molar ratios of 15, 30, 50 and 70. Pressure versus oil volume is plotted in figure 21. Pressure-composition (P-X) diagram represents quality lines as liquid percents in the swollen oil were shown (Fig. 22). Swelling factor and mixture oil density as a function of added solvent: oil mole percent are plotted (Figs.

Table 4. Comparison of experimental data of hydrocarbon swelling test with EOS predicted values, reservoir oil sample of Pb = 1800 psia, at 206 °F, Ragua oil field, well no. E40.

Fluid	LPG/DG mole %	Saturation pressure psia	Predicted saturation pressure psia	Swelling factor	Mixture density g/cc
Resvoir oil	0.000	1800	1801	1.000	1.000
Mixture # 1	15.24	2263	2206	1.115	1.115
Mixture # 2	30.40	2702	2624	1.288	1.283
Mixture # 3	50.46	3195	3154	1.682	1.672
Mixture # 4	70.41	3676	3462	2.652	2.639
Mixture # 5	85.24	4006	3197	5.072	5.347

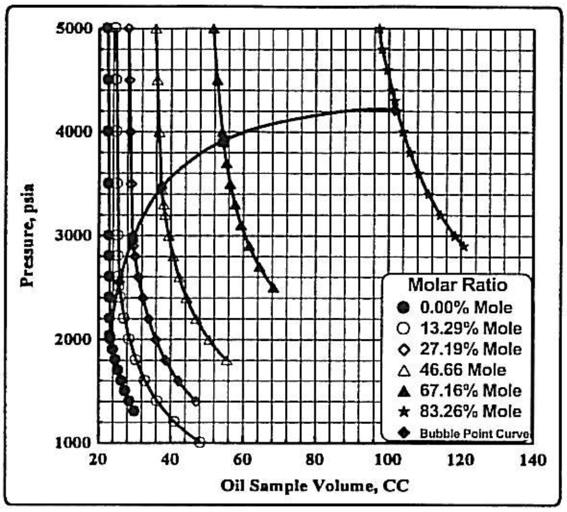

Fig. 19. Pressure – volume relations obtained from swelling of reservoir oil 2035R with 35% LPG+65%DG solvent at different LPG/DG – oil molar ratio.

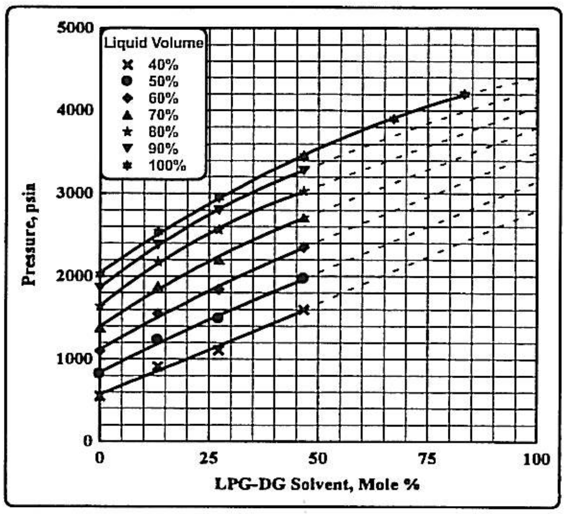

Fig. 20. Swelling test, quality lines, P_b2030 pia with 35% LPG+65% DG solvents at different LPG/DG oil molar ratio.

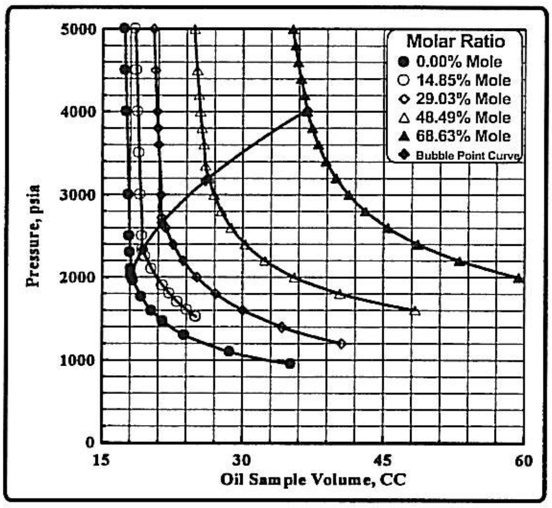

Fig. 21. Pressure – volume relations obtained from swelling of reservoir oil 2035R with CO_2 at different CO_2 oil molar ratio.

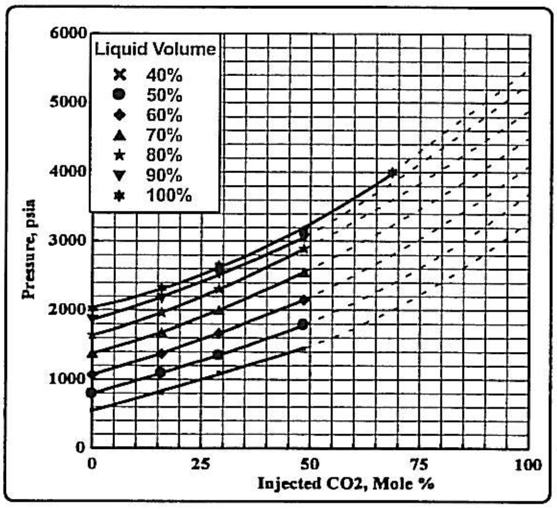

Fig. 22. Swelling test, quality lines, P_b = 2030 psia ith CO_2 at different CO_2 oil molar ratio.

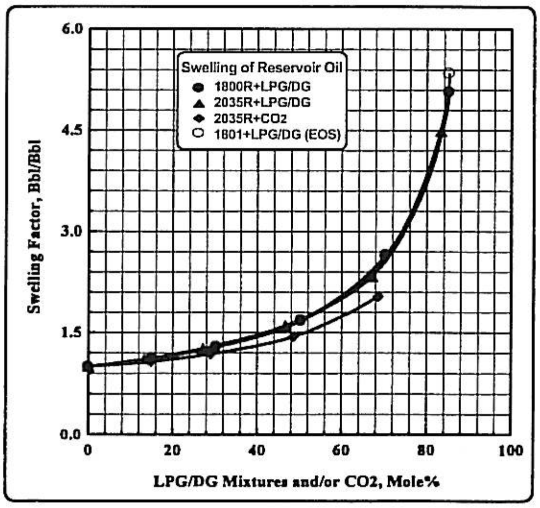

Fig. 23. Swelling factor for reservoir oils after injection of LPG/DG and / or CO_2 at 206 °F.

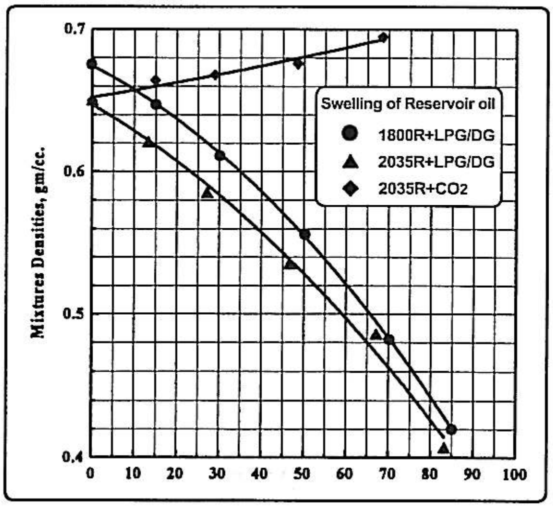

Fig. 24. Mixture densities for reservoir oils after injections of LPG/DG and / or CO_2 at 206 °F.

Table 5. Summary of hydrocarbon swelling test at 206 °F for reservoir oil sample of P_b = 2035 psia, Ragua oil field, well no. E40.

Fluid	LPG/DG mole %	Saturation pressure psia	Swelling factor	Mixture density g/cc
Resvoir oil	0.000	2035	1.000	0.6502
Mixture # 1	13.29	2551	1.106	0.6209
Mixture # 2	27.19	2965	1.262	0.5853
Mixture # 3	46.65	3465	1.601	0.5355
Mixture # 4	67.15	3915	2.333	0.4861
Mixture # 5	83.26	4215	4.489	0.4071

Table 6. Summary of carbon dioxide swelling test at 206 °F for reservoir oil sample of P_b = 2035 psia, Ragua oil field, well no. E40.

Fluid	LPG/DG mole %	Saturation pressure psia	Swelling factor	Mixture density g/cc
Resvoir oil	0.000	2035	1.000	0.6500
Mixture # 1	14.90	2336	1.068	0.6641
Mixture # 2	29.00	2657	1.181	0.6681
Mixture # 3	48.50	3172	1.436	0.6760
Mixture # 4	68.50	4015	2.036	0.6947

23 - 24). The summary of CO_2 swelling results carried out on the reservoir oil sample of P_b = 2035 psia are shows in Table 6.

Swelling factors for both oils are almost identical when LPG/DG solvent is used for swelling. However, swelling factor for oil P_b = 2035 psia using CO_2 appears to become lower compared to that obtained with LPG/DG solvent when the molar percent is increased as shown in figure 23.

Swollen mixtures density for both oils of pressure 1800 psia and 2035 psia decreases when the added molar ratio of LPG/DG solvent is increased. While swollen mixture's density for oil of P_b pressure 2035 psia increases as the molar ratio of CO_2 added is increased as illustrated in figure 24. Accordingly, sweep efficiency for the displaced oil by CO_2 expected to have an advantage compared to that with LPG/DG solvent when the miscibility conditions are satisfied.

CONCLUSIONS

1. Solvent mixture of a molar ratio LPG/DG 40/60 was found as the MMC with oil of P_b= 1800 psia, at the injection pressure of 1855 psia at 206°F. Obviously the minimum miscibility composition value was over estimated by the EOS for this oil (LPG/DG: 55/45).
2. Solvent mixture of a molar ratio LPG/DG: 35/65 was found as the MMC at injection pressure of 2100 psia for reservoir oil P_b=2030 psia at 206°F. The minimum miscibility composition was also overestimated by the EOS for this oil (LPG/DG: 50/50). However, more work should be performed in order to understand the actual reasons for these phenomena for both oils.
3. The oil recovery mechanism for both oils (P_b =1800 psia and 2030 psia) was found to be a multiple contact condensing drive mechanism when displaced by LPG/DG solvent at miscibility conditions.
4. The MMP of CO_2 for reservoir oil of bubble point pressure of 2030 psia was experimentally determined to be 2710 psia at reservoir temperature of 206°F. The mechanism of oil recovery was a vaporizing drive. MMP of CO_2 was also calculated using Glaso[12] correlation for pure CO_2 for comparison and was found to be equal to 2667 psia, which shows good agreement with the experimental results.
5. Swelling factor values predicted by EOS match very well with the data experimentally obtained for five additions of LPG/DG mixtures into oil reservoir P_b = 1800psia.

6. Predicted saturation pressures using EOS modelling are in a good match with the experimental data when the molar percent of LPG/DG is *50%* and lower. At a higher molar percent, the predicted saturation pressures are under estimated.
7. Swollen mixture density for both oils of P_b pressure 1800 psia and 2035 psia decreases when the added molar percent of the LPG/DG solvent is increased.
8. The swollen mixtures density for the oil of P_b pressure 2035 psia increases as the molar percent of the CO_2 added is increased. Therefore, sweep efficiency for the displaced oil by CO_2 expected to have an advantage compared to that with LPG/DG solvent when the miscibility conditions are satisfied.

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