Petroleum Res. J. Vol. 12 (2000); P. 9-18, 13 Figs.

Implementations of Enhanced Oil Recovery Techniques in the Arab World are Questioned?

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التساؤل عن تطبيقات تقنيات الإسترداد الإضافي للنفط في الوطن العربي؟

علي حبيب الخفاجي

في العام 1998، قُدر الاحتياطي النفطي العالمي بحوالي 1051,74 مليار برميل وقُدر الاحتياطي العالمي للغاز الطبيعي بحوالي 152,5 تريلين متر مكعب. وتتواجد كميات كبيرة جدا من هذه المواد الهيدروكربونية الطبيعية المولدة للطاقة في الوطن العربي وخاصة في منطقة الخليج، قدرت بحوالي 61% (643,41 مليار برميل) من الاحتياطي العالمي للنفط و21% (32,6 تريليون متر مكعب) من الاحتياطي العالمي للغاز الطبيعي. وعلى العموم، فإن حوالي 70% من هذه المواد الهيدروكربونية المكتشفة تبقى في المكامن حيث تتخلف في باطن الأرض وذلك بعد عمليات الإنتاج التي تعتمد بالدرجة الأولى على طرق الاستخراج الاعتيادية الشائعة. وهناك عوامل رئيسة متعددة تسبب بقاء المواد الهيدروكربونية في باطن الأرض ومنها الاختلاف الطبقي، قوى الضغط الشعري، طريقة إكمال الآبار، انخفاض الضغط في المكامن وغيرها من العوامل التي تؤثر على كفاءة استخلاص البترول من باطن الأرض.

إن الهدف الرئيسي لهذا البحث هو إبراز أهمية تطبيق طرق الاسترداد الإضافي للنفط والدور المهم الذي تلعبه في زيادة نسبة الاستخلاص للنفط والذي يؤدي بالتالي إلى إيرادات إضافية وإلى إطالة عمر الإنتاج. وتم توضيح ذلك بأمثلة أخذت من الاختبارات المعملية والميدانية بهذا الخصوص. وعلى سبيل المثال عند زيادة نسبة الاستخلاص بمقدار 1% من الاحتياطي النفطي الأصلي في الوطن العربي سيؤدي إلى إيرادات إضافية تقدر بـ 536 ألف مليون دولار حسب الأسعار السائدة 25 دولاراً للبرميل بالإضافة إلى الزيادة في عمر الإنتاج بحوالي ثلاث سنوات إستناداً إلى معدلات الإنتاج السائدة حالياً (20 مليون برميل/اليوم). وعليه بات من الضروري القيام بالبحوث والدراسات المتطورة والواعدة وتطوير مناهج الدراسات والتطبيقات العملية لتقنيات الإسترداد الإضافي في وطننا العربي لتحقيق الزيادة في نسبة الاسترداد الإضافي من هذه الثروة الهيدروكربونية الناضبة.

Abstract: *At the end of 1998, the proven world oil reserve is estimated as1051.74 milliard barrels and the natural gas reserve as 152.5 trillion cubic meters. A tremendous amount of these natural resources of energy is deposited in the Arab World, especially in the Arabian Gulf. About 61% (643.41 milliard barrels) of the world oil reserve and 21% (32.613 trillion cubic meters) of the world natural gas reserve are allocated in the Arabian countries. In general, about 70% of the hydrocarbon resources remain in the underground petroleum reservoirs after conventional recovery methods of production. Several factors, such as reservoir heterogeneity, capillary forces, well completion and pressure decline, are affect the hydrocarbon recovery efficiency.*

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The main objective of this research is to emphasize the importance of Enhanced Oil Recovery (EOR) techniques and their role to increase the percentage of oil recovery. Some examples of experimental work done in this aspect are demonstrated. Indeed, an increament of only 1.0% of the Original Oil in Place (OOIP), in the Arab World for example, results an additional income of about 536 milliard US dollars at a current oil price of $25 per barrel. Also, on the bases of 20 million barrels/day oil production rate, an additional production life of about three years will be achieved. Therefore, It becomes increasingly necessary to establish sophisticated research and development programs for study and implementation of the enhanced oil recovery techniques.

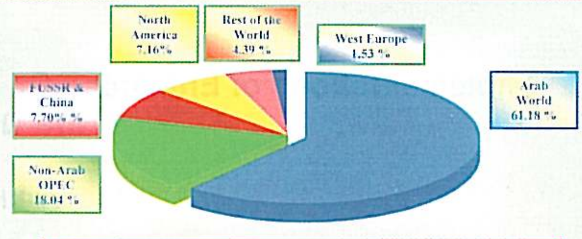

Fig. 1 World oil reserve @ the end of 1998, 1052 milliard barrels.

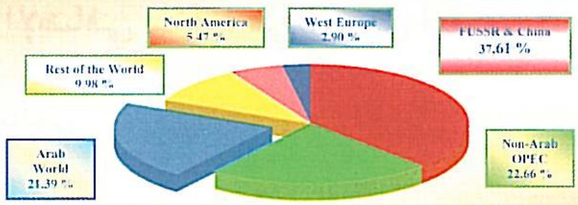

Fig. 2 World gas reserve @ the end of 1998, 152504 milliard cubic meters.

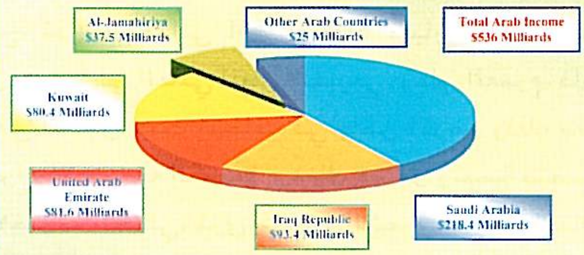

Fig. 3 Arab world additional income if oil recovery increased by 1.0 % of OOIP.

INTRODUCTION

Proven oil reserve in the Arab World is approximately equal to 643.41 milliard barrels. This forms about 61.18 % of the total oil reserve in the world as shown in Fig. 1[1,2,3]. The Arab natural gas reserve is 32.613 trillion cubic meters, which forms 21.38% of the total world gas reserve[1,2,3] as illustrated in figure 2. However, about 30% of the original hydrocarbons in place could be recovered using the conventional production methods. Therefore, about 1500 milliard barrels of oil and 76.1 trillion cubic meters of the natural gas will be left unrecoverable. Enhanced Oil Recovery Techniques (EOR) should be thoroughly investigated and implemented to achieve an ultimate hydrocarbon recovery. Also, the production life of reservoirs will be prolonged. This is a strategic target to support the national income to develop Arab countries. If the oil recovery in the Arab World is increased, for example, by 1% of the OOIP, the additional amount of oil that will be produced is equal to 21447 million barrels. Life of production will be prolonged by about three years at a daily rate oil production of 20 million barrels. An additional income at the current oil price of $25/barrel will be about $536 milliards (Fig. 3). In order to produce as much as possible of the remaining hydrocarbon in the petroleum reservoir, one should enable hydrocarbon to flow toward the production wells by improving the volumetric sweep and the displacing efficiencies utilizing a proper EOR method. Accordingly, it becomes urgently demanded to give a high priority for (EOR) research and development programs.

HYDROCARBON RECOVERY METHODS

Petroleum recovery may be classified as Primary Recovery Methods, Pressure Maintenance Methods (Secondary) and Enhanced Oil recovery Methods (Tertiary). When the reservoir is producing by its natural energy, this stage of production is referred to as Primary Recovery Methods. Pressures Maintenance Methods are usually applied by injection of either water, gas or both into the reservoir to maintain the reservoir pressure at a desirable level. The primary and pressure maintenance methods of production may be categorized as the Conventional Recovery Methods. Applying the conventional methods, the ultimate recovery is estimated as 30% of the OOIP. However, the most promising methods to increase the recovery are the Enhanced Oil Recovery Methods.

Primary Recovery Methods

These methods depend upon the natural energy prevailing in the petroleum reservoir that provides a drive mechanism for hydrocarbon production. These drive mechanisms fall in three categories; dissolved gas drive, gas cap drive, and natural water drive. Dissolved gas drive reservoirs exhibits: a rapid pressure decline, a low produced gas oil ratio (GOR) at the early life of production. (GOR) increases to a maximum value then declines at later production stages. Water cut is small, and the expected oil recovery is 5-10% of the OOIP. In the gas cap drive reservoirs, pressure declines gradually and continuously, (GOR) is higher in the wells produced near the gas-oil contact, water production is negligible and the expected recovery is 15-30% of the OOIP. Characterization of the water drive reservoirs is that the reservoir pressure declines at a low rate, (GOR) remains close to the initial value, water production increases with time and the expected oil recovery is from 30-50% of the OOIP. From the practical experience, only 30% of the OOIP can be recovered during the primary methods of production[4]. Hence, about 70% of the OOIP remains unrecoverable.

Pressure Maintenance Methods

Either water or gas is injected into the petroleum reservoirs to maintain the pressure at a required level. Water flood is applied worldwide since the dawn of the oil industry due to economic considerations and simple technical application. In spite of the worldwide application of water flood, a great amount of oil remains unrecoverable because of the areal sweep efficiency, the contact factor, and displacement efficiency.

Areal Sweep Efficiency

Areal sweep efficiency is defined as the area of the reservoir portion that is flooded by the injected water for a given production pattern[5]. This efficiency depends upon the well pattern, well spacing and the mobility ratio (M). Mobility is the ratio of the relative permeability of the flowing fluid to its viscosity. Hence, the mobility ratio is the mobility of the displacing fluid (water) to the mobility of the displaced fluid (oil). When the mobility ratio is one or less, water will push against the oil in a piston like manner. This mobility is referred to as favorable mobility ratio. When the mobility ratio is ten and greater (unfavorable), the water will traverse the oil leaving a large amount behind the flooding front and in turn reduces the recovery factor. Unfavorable mobility ratio occurs at a low viscosity and a high permeability of the displacing fluid and also at a high viscosity and a low permeability of the displaced fluid. Reduction of the oil viscosity and elevation of water viscosity will improve mobility ratio toward the favorable value and thus increase the oil recovery.

Contact Factor

It is defined as the portion of the reservoir that is swept and contacted by the water in the flooded zone[5]. It was evident that not all of the rock in the flooded area is contacted by water due to the reservoir rock heterogeneity, which in turn reduces the oil recovery.

Displacement Efficiency

Although the injection water contacts the reservoir rock, a high percentage of oil remains in the reservoir due to inefficient pore-to-pore displacement (Fig. 4). Consider a doublet model composed of two different capillaries previously filled with oil[5]. At the beginning of water injection, the water evenly displaces the oil at the inlet of doublet, (Fig. 4-A). Further water injection results in a complete oil displacement in the small capillary and part of the oil in the large one, (Fig. 4-B). At the end of the flood, the injected water locks the back door of the large capillary and traps the oil under equilibrium capillary pressures exerted at both ends of the doublet, (Fig. 4-C). The pressure gradient needed to unlock the trapped oil is usually very large due to the interfacial tension at the water-oil interface.

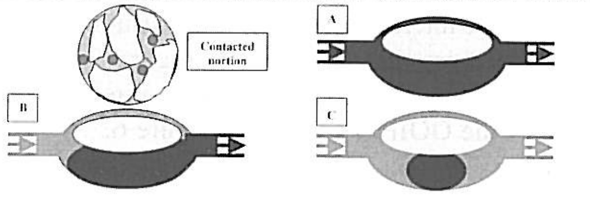

Fig. 4 Doublet capillary model for oil displacement.

ENHANCED OIL RECOVERY TECHNIQUES

The remaining oil after the conventional oil recovery methods (primary and pressure maintenance) is the target for the Enhanced Oil Recovery Techniques (EOR). Two main factors affect improvement of oil recovery. Firstly, the reduction of the interfacial tension at the interface of the injected fluid and the reservoir oil and secondly, reduction of the mobility ratio of the flowing fluids in the flooded portion and the oil zone of the reservoir. Essentially, there are three major EOR methods to achieve the above objectives. These methods are chemical flooding, miscible flooding and thermal recovery method, which are implemented worldwide to improve oil recovery.

Chemical Flooding Method

Chemical flooding is comprised of two mechanisms: either, by reducing the interfacial tension at the water-oil interface using surfactants or reducing mobility ratio by adding low concentration of polymer (synthetic polymers-polyacrylamide or biologically produced polymers -polysaccharide) into the injected water to increase its viscosity and in turn improve oil recovery. A surfactant (surface-active agent) has a dual function, the hydrophilic and the lipophilic properties that enable it to reduce the interfacial tension into an ultra-low value at the water-oil interface. Surfactants may be mixed with the injected water at the surface, or may be generated in-situ in an alkaline flooding. In-situ surfactant generation occurs when alkaline chemicals such as sodium hydroxide and/or sodium orthosilicate react with petroleum acids, provided sufficient amount of these acids are available in the reservoir oil. Also, surfactants improve oil recovery by oil emulsification and wettability alteration mechanisms. Addition of a surfactant aqueous solution composed of 50% anionic and 50% nonionic with 0.6% by weight concentration reduces the interfacial tension to an ultra-low value of 0.035 dynes/cm as shown in figure 5, hence, increases the oil recovery to a great extent (about 70% of the OOIP) as shown in figure 6.

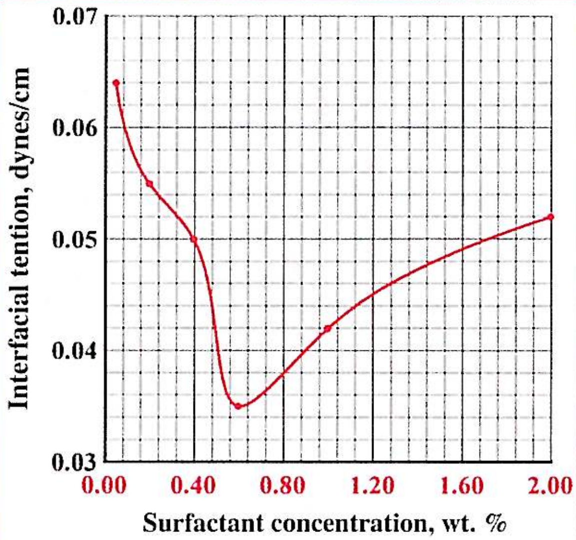

Fig. 5. Interfacial tention as a function of the surfactant concentration.

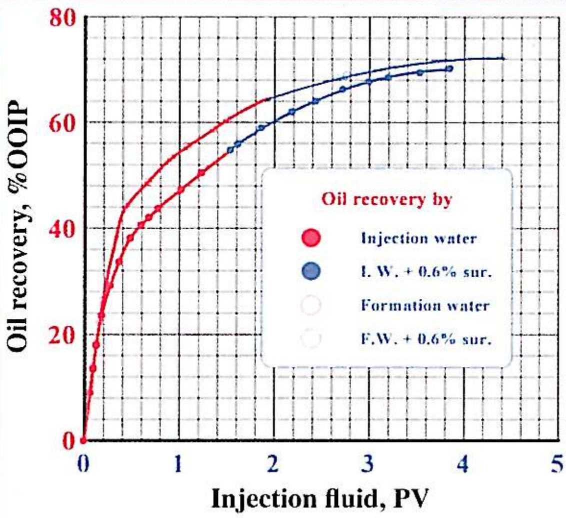

Fig. 6. Oil recovery as a function of injected water and formation water with and without sufactant.

Miscible Flooding Method

This method depends on injection of hydrocarbon and non-hydrocarbon fluids into the reservoir, in which the injected fluids will be mixed at all proportions with the reservoir oil at the prevailing reservoir conditions. As a result, the interfacial tension between the injected fluid and the reservoir oil will be eliminated. When this occurs, about 100% of the oil contacted by the injection fluid will be displaced and recovered. 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), and the multiple-contact miscible (MCM) process (dynamic miscibility processes). In the first contact miscible process, solvents of liquefied petroleum gas (LPG) mix directly with reservoir oil in all proportions and their mixtures always remain in a single phase. In the multiple-contact miscible process, 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. MCM is of three kinds: the condensing, the vaporising and the condensing/vaporising miscible processes.

In a multiple contact condensing drive mechanism, the hydrocarbon intermediate compounds (C_2-C_6) in the injected solvent condense into the reservoir oil until a sufficient quantity of this solvent exists at the displacement front to cause miscibility with the oil. Minimum miscibility composition (MMC), for example, of LPG/Dry Gas mixture was determined experimentally using the slim tube displacement technique[6,7]. Results graphed (Fig. 7) indicate that about 100% of the OOIP is recovered.

In the vaporising drive, for example (CO_2), the injected fluid will extract 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. The minimum miscibility pressure (MMP) is experimentally determined[6,7] and illustrated on figure 8. Again, about 90% of the OOIP is recovered by CO_2 injection. In the above investigation, Peng-Robinson cubic equation of state (EOS) modelling was also applied to predict the MMC and MMP using the Computer Modelling Group (CMG PROP) software.

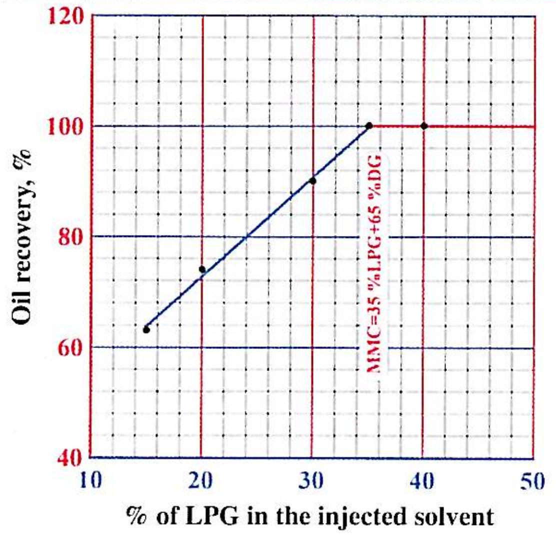

Fig. 7. Oil recovery as a function of % LPG for oil sample of BPP = 2030 psia, Raguba Oil Field, Well No. E-40.

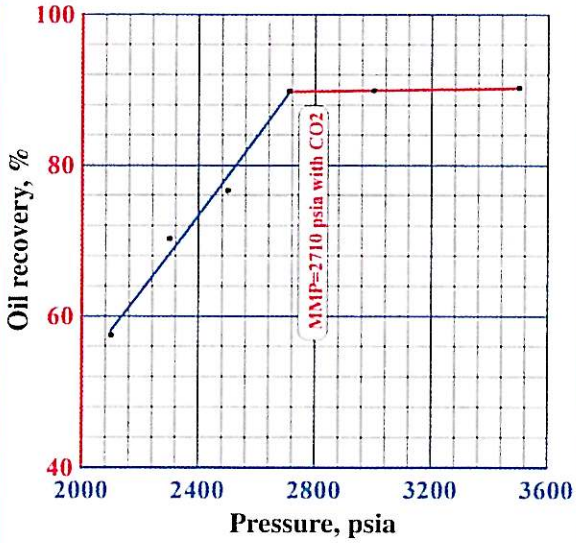

Fig. 8. Oil recovery vs pressure for oil sample of BPP = 2030 psia with CO_2, Raguba Oil Field, Well No. E-40.

Thermal Recovery Methods

Thermal recovery methods such as *in-situ* combustion, hot water and steam are used to increase the reservoir oil temperature and hence reduce appreciably the oil viscosity, reduce the interfacial tension, increase oil relative permeability, decrease the water relative permeability, increase irreducible water saturation and decrease residual oil saturation. Effects of heat on the above mentioned parameters improve the mobility ratio and increase the oil recovery factor. On the contrary to other fluid injection methods, heat has the ability to transfer throughout the reservoir by conduction and convection, hence subjected most of the oil reservoir portions to the heat effect. This is an additional advantage of thermal recovery methods compared to other EOR methods. In the in-situ combustion, air or oxygen is injected in to the reservoir that reacts with the oil and generates heat and in turn increase the reservoir temperature until a spontaneous ignition occurs and the combustion front moves toward the production wells. Forward in-situ combustion takes place when the combustion front flows in the same direction of the reservoir fluid flow, while in the inverse combustion, the combustion front flow opposite the reservoir fluid flow.

Steam injection is of two kinds: the first kind is the steam drive processes, in which steam (about 80% steam quality) is injected into a well and the oil is produced at another. The second kind is the steam soak processes, in which steam is injected into an oil well for a period of time ranges from few days to few weeks, then, oil production will be resumed from the same well. Steam injection is one of the most famous thermal recovery methods applied to enhance oil recovery from petroleum reservoirs containing heavy and intermediate oil of higher viscosity. Figure 9 shows a schematic diagram for hot water and steam flooding apparatus[8]. Figure 10 represents oil recovery versus hot fluids injected in pore volumes. In a hot water (at reservoir temperature -30 °C) displacement experiment, oil recovery is found to be 15% of the OOIP. When this experiment is followed by injection of steam at temperature of 170 °C, oil recovery is increased to 60%. About (28%) oil recovery is obtained by injection of hot water at 120 °C. A highest oil recovery (71%) was achieved by steam injection at 170 °C. It appears that when steam injection is initially applied for heavy oil recovery processes, a higher oil recovery will be achieved as illustrated in figure 10.

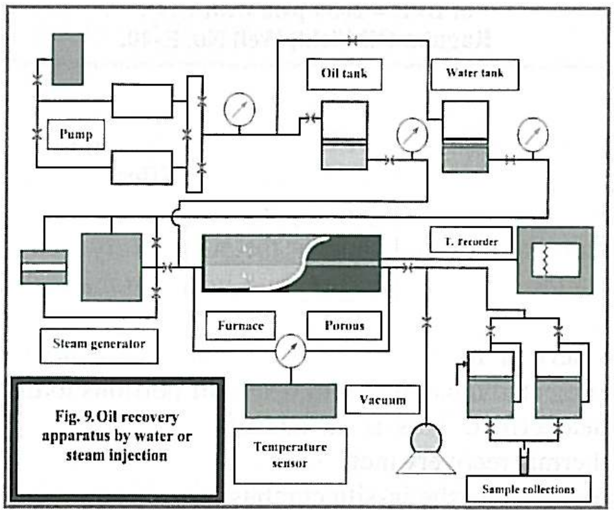

Fig. 9. Oil recovery apparatus by water or steam injection

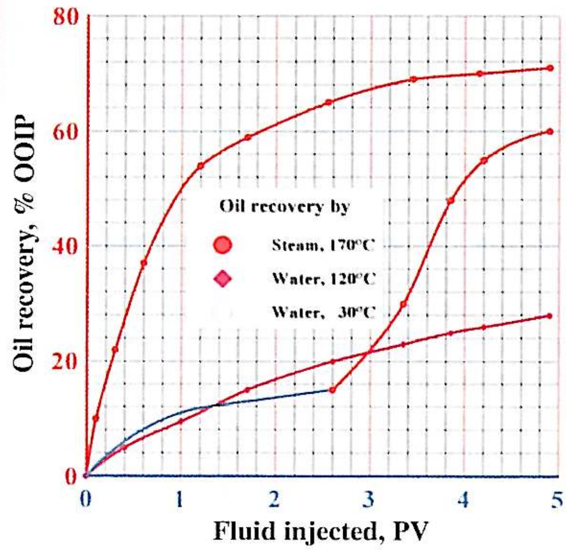

Fig. 10. Oil recovery as a function of hot fluid injection.

In-situ Foam Generation

One of the most important problems of steam injection is the override due to the high differences in the steam and oil densities and channeling through high permeable zones because of the very low steam viscosity compared to that of oil. Accordingly, steam will break through early at the producing wells resulting in poor sweep efficiency. To avoid these problems, surfactant solution was injected prior to steam injection. When steam is encountered with the surfactant solution, foam will be generated. Foam is a dispersion of a large volume of gas in a small volume of liquid phase in such away that the gas is the discontinuous phase and the liquid is the continuous phase. Simply, foam is a soap bubble filled with gas and bounded by a thin film of liquid in which gas volume is greater than 94% of the total volume of the system. Foams apparent viscosities are higher than either the liquid or the gas of which they are composed. Therefore, steam flow will be hindered instantaneously due to foam generation in the portions of the reservoir where over ride and/or thief zones exist.

Surfactants used in steam flooding should be able to tolerate the high temperature of steam. Consequently, a surfactant having thermal stability is required. Much of commercial surfactants failed the thermal stability test at 200 °C and pressure of 500 psia[9,10]. Suntech Group manufactured several surfactants to be used in steam processes. Among nine surfactants, Suntech IV was found superior to fulfill the thermal stability requirement in addition to its ability to generate foam and reasonable phase partitioning with reservoir oil. The half-life time of Suntech IV was about two years[9,10].

Surfactant adsorption on sand grains surfaces with and without clay (Kaolinite) and phase partitioning with heavy oleic phase was thoroughly studied. The isothermal adsorption exhibited a Langmuirian model (Fig.11). Schematic diagram of oil displacement apparatus by foam and steam was designed (Fig. 12). An appreciable increase in oil recovery would be obtained when foam was generated ahead of the injected steam front in the porous medium[10].

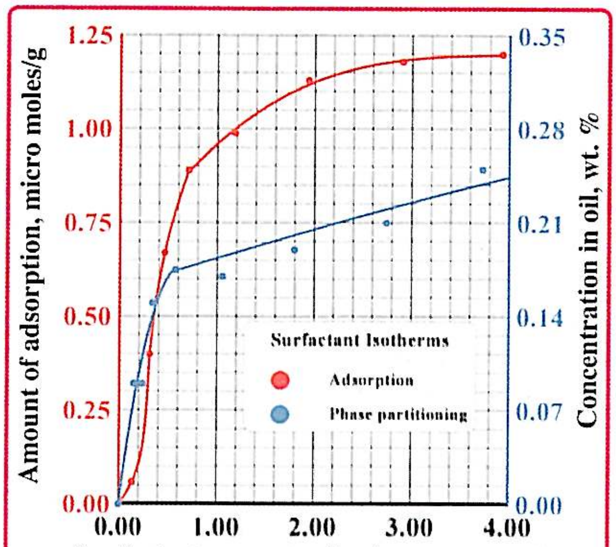

Fig. 11. Adsorption and phase partitioning isotherms of surfactant.

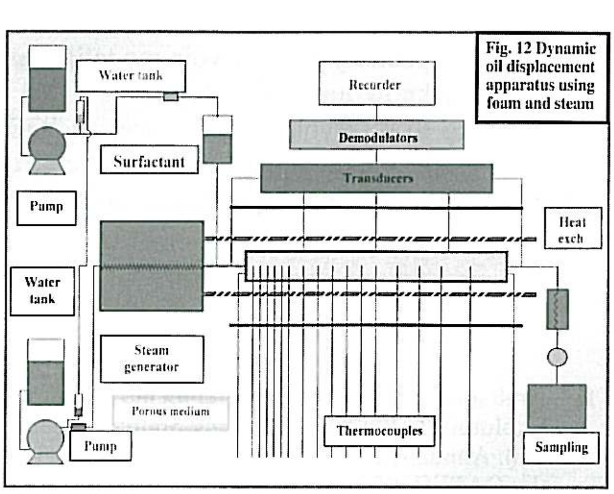

Fig. 12 Dynamic oil displacement apparatus using foam and steam

ENHANCED OIL RECOVERY IN THE ARAB WORLD

Most of the produced oil in the arab world depends on the natural energy. Pressure maintenance by gas and/or water injection is applied to some oil fields. Implementations of EOR are stile in the beginning except the miscible projects in Intisar "D" oil field in Al-Jamahiriya and Hassi-Masood oil field in Algeria. Intisar "D" oil field is one of the largest miscible gas injections in the arab world and internationally. Intisar "D" oil field project is a good example of an EOR miscible method implementation. About 70% of the original oil in place is recovered in this field by miscible gas injection. Accordingly, a first priority and a high attention should be given to EOR implementations, since about 1500 milliard barrels of oil will be left unrecoverable after applying primary and secondary oil recovery methods. A higher percentage of the unrecoverable oil is expected to be produced by implementation of the EOR technology.

PLANING FOR ENHANCED OIL RECOVERY PROJECT

Implementation of an IOR and/or EOR project to an oil reservoir requires programs of preparation for reservoir studies, and providing necessary data that are needed to enable selection of a proper method for increasing oil recovery. Figure 13 represents a general flow chart for this purpose. First, one should consider the reservoir and injection conditions of pressure, temperature, injection and production rates, number of wells, well pattern, pay zone thickness, formation geology and method of well completion. Second, provides experimental data pertained to physical and chemical properties of the reservoir fluids such as viscosity, density, interfacial tension, compressibility, and thermodynamic properties-PVT for the reservoir fluids. Also, provides data concerning physical and chemical properties of the reservoir rock, such as porosity, permeability, rock compressibility, wettability, fluid saturation, capillary pressure, resistivity and geological evaluation of the formation rock. In addition, provides thermal properties of reservoir fluids and reservoir rock should be studied, i.e. thermal expansion, conductivity, and specific heat determination.

In light of the above and any other necessary information, and using a proper screening criterion, a recovery method may be recommended to the reservoir of interest. A screening guide usually contains basic information of reservoir fluids and reservoir properties as viscosity and API gravity of the oil, formation water salinity, depth and thickness of the pay zone, reservoir temperature, rock porosity, permeability and transmissibility and the type of the reservoir rock. Accordingly, immiscible gas and/or water injection methods may be applied for pressure maintenance (secondary recovery) and improving oil recovery, or an appropriate miscible, thermal, and/or chemical method may be recommended to enhance oil recovery (tertiary recovery). The following studies have become necessary: study the petro-physical properties of the reservoir fluids and rocks, conduct experimental work pertains to the selected or proposed EOR method, apply the available geological and reservoir simulators, and predict the future reservoir performance after the history matching is done. Then, a pilot test should be applied in the field of interest, to examine the success or failure of the project in order to decide a full-scale application of the project. Enhance oil recovery is a heavy task which needs a great deal of efforts and time to accomplish. Planning to start such program as early as possible becomes very essential.

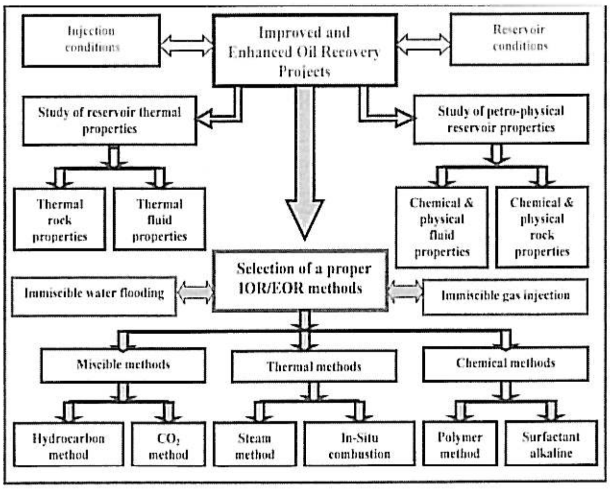

Fig. 13. Flow-chart for selection of an improved oil recovery and/or an enhanced oil recovery project.

CONCLUSIONS

In this investigation, oil recovery laboratory experimental work carried out, using different EOR methods demonstrate the following conclusions:

1. Oil recovery is significantly increased (about 70% of the OOIP) by injection of surfactant aqueous solution composed of 50% anionic and 50% nonionic with 0.6% by weight concentration.
2. Miscible displacement experiments show that 100% oil recovery using LPG/dry gas mixtures, and about 90% using CO_2 solvent could be achieved.
3. A higher oil recovery (about 71% of the OOIP) is obtained when steam injection is initially applied for a thermal oil recovery as compared to (60%) oil recovery obtained when steam is applied after water flooding.

RECOMMENDATIONS

Because of the huge amount of reservoir oil that will remain (about 1500 milliard barrels) after conventional production method application, it becomes necessary to give the IOR and/or EOR methods a high priority and consideration for the research and development. Chemical, thermal and miscible methods should be thoroughly investigated to determine the most effective method that may be applied to enhance oil recovery in the oilfields of the Arab World. Therefore, the following crucial recommendations are suggested for future planning to activate EOR technology in the Arab World.

1. Document all information, and develop programs for exchange experience.
2. Collaborate with the existing petroleum research centres in the Arab World and avoid research duplication. Also, co-operate with the international petroleum research centers for exchange of experience, scientific visits and training, especially in reservoir modeling as well as the know-how technology.
3. According to reservoir performance, an IOR and/or EOR method should be recommended for early or lately implementation in the life of a reservoir.

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