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INJECTION OF LEAN GAS INTO AN ULTRALIGHT OIL BEARING RESERVOIR: INTERFACIAL ASPECTS

ABSTRACT

Application of lean gases, particularly a methane rich gas, nitrogen, carbon dioxide, air and their mixtures in an ultra light oil bearing reservoir located in Southern Hungary, is in an advanced stage. The relevant studies and mathematical simulations have definitely indicated a substantial surplus oil production and it was also revealed that gravity segregation and vaporization of light hydrocarbons were the main elements of the displacement mechanism. However, well founded arguments have arisen about anomalous interfacial phenomena and precipitation of some oil constituents during the recovery process since the oil was strongly paraffinic and the predicted vaporization was high. Therefore, a detailed laboratory study was commenced to determine the effect of nitrogen, carbon dioxide and lean methane on surface and interfacial properties. On the basis of the experimental results, it was concluded that the well known surface and interfacial effects, like enrichment of asphaltenes, resins and heavy hydrocarbons at interfaces, can be neglected when lean and non-reactive gases are injected into an ultra light bearing reservoirs. On the other hand, the precipitation of paraffins and other waxes at oil/water interface may take place even at very low vaporization in both the reservoir space and the surface facilities. Since that interfacial, probably catalyzed phenomena is newly recognized, further laboratory and field studies are needed to elucidate its detrimental effects on recovery efficiency, well performance and surface technology.

INTRODUCTION

Some years ago, summarizing laboratory and field results, Espie et al. [1] have firmly pointed out that injection of lean gases to volatile oil reservoirs is an attractive recovery option. The method, based on large-scale gas recycling of hydrocarbon gases, may be validated in field scale model and vaporizing the residual oil from gravity drainage improves significantly the recovery factor. A little bit earlier Saidi et al. [2] has also confirmed that lean gas injection is also capable of mobilization of residual oil after water flooding in fractured reservoirs. The lean gas injection into ultra light oil or condensate bearing reservoirs is, however, not free of difficulties. As it was stated by Pires et al. [3] a major challenge in case of gas-condensate reservoirs is to avoid the drop-out of heavy fractions, and in this respect there is no significant difference between the nitrogen and methane injection [4–5].

Despite similar results at large, the detailed analysis of factors influencing the recovery factor, additional and valuable observations were reported. For instance, Newley and Begg [6] reported that small-scale heterogeneity may unfavorably influence the vaporization phenomena decreasing the ultimate recovery by up to one third of that obtained in uniform systems. Although this conclusion was based on simulation, the fact that we should pay attention is that even physical parameters (porosity, pore size distribution etc.) of the reservoir might be responsible for shaping of the efficiency of lean gas injection.

According to a survey by Arevalo [7] a restructuring in gas injection projects has been taken place during the past decades: in 1971 the injection of CH gases comprised 96 % of all field operations, while their share was less than 25 % in the eighties. Similarly, the application of different gases aimed mostly at improving the segregation and gravity drainage instead of conventional displacing roles of gas media. In this respect the field experiences, showing extremely high recovery factor [8–10], give satisfaction to Cardwell and Parsons who as early as 1946 developed a theoretical concept for vertical segregation and proposed creation of artificial gas cap to produce roof (attic) oil from reservoirs having high vertical permeability, density difference between fluids and low oil viscosity as early as the forties. After all, the inert gases, including air and other oxygen-containing ones, came to the front of field application but they also raised new problems to be solved. Among others, Droege et al. [11] disproved the belief on chemical inertness in oxygen-containing system (even in case of CH_4 and O_2) at low reservoir temperature. Further, it was demonstrated that the oxygen may react not only with the component of oils, but also with constituents (pyrite) of rocks [12] and formation water. Despite these experimental facts, the following statements are still generally accepted and influential today:

- at low reservoir temperature and in light oil reservoirs the chemical interaction between the oxygen-containing media and the oil is negligible and it has no impact on recovery factor, and
- at high reservoir temperature and in heavy oil bearing system the oxygen consumption is high, sometimes complete, the physical and chemical properties of oil change significantly, and hence, the recovery factor are highly dependent on these interactions [e.g. 13–18].

Consequently, the converging conclusion is that injecting unsaturated lean CH, inert or oxygen-containing gases into light oil and condensate reservoirs the positive effects might be exclusively attributed to segregation and vaporization, meanwhile the chemical reactions and their consequences are negligible [19–20].

Surveying the literature data it is surprising that none of the papers deals with the surface and interfacial consequences of the vaporization, although the loss or removal of light hydrocarbons logically imply measurable change is these properties and if that is so, the capillary and flow phenomena, residual oil saturation etc. should also be changed. Indirectly, these factors may influence the recovery factor, consequently the study of surface chemistry in such system is not in vain. Recognizing this gap in fundamental and applied research, the primary aim of laboratory studies was to clarify the potential effect of changes in surface and interfacial properties and to predict their role in IOR/EOR technologies.

PRACTICAL INITIATIVES OF THE RESEARCH PROGRAM

The largest Hungarian oil and gas reservoir system is the Algyő field consisting of more than 70 hydrodynamic units. Beside conventional saturated oil bearing layers there are also some reservoirs which contain undersaturated and ultra light oils or gas condensate. One typical representative of the later systems is the Tisza-1 reservoir locating in the uppermost section of the Algyő formation (see **Table 1.**). The ultra light oil has been produced from that layer since 1992 and with gradually declining pressure (max. 6.5 bar), 24 % recovery factor was attained. The main element of the displacement mechanism was the strong bottom water drive.

Table 1.

Main parameters of the Tisza-1 reservoir

OOIP	1521 10^3 m^3
Area	4.96 km^2
WOC	1643 m subsea
Net pay	
Oil zone	12.6 m
Bottom water zone	6.5 m
Temperature	92 °C
Initial pressure	169 bar
Porosity	28.3 %
Permeability	804 mD

The present oil recovery factor is, however, much less than the value (48%) predicted by 3D full field simulation. Similarly, the ultimate recovery of the intermediate components was nearly the same as the predicted oil recovery. To enhance both factors and to accelerate the production rate, injection of lean hydrocarbon gas at the rim was evaluated as a realistic alternative. The basis of that option is that contacting a dry gas with the ultra light oil a substantial vaporization is resulted and the enriched gas might strengthen the segregation and gravity drainage at the top of the reservoir. The advantages of this mechanism were fully proved by compositional field simulation. The results of mathematical modeling have shown 10–13 % additional recovery in C_3–C_6 components, meanwhile the effect on oil production was also positive [21].

The feasibility of the above mentioned reservoir engineering concept was supported by the available infrastructure on site. The only doubtful element of the technology is the utilization of a valuable hydrocarbon gas. Therefore, application of other, particularly inert gases, was also considered. The high vaporization loss in the reservoir raised also some questions concerning the properties and behavior of oil/water/gas/rock systems. Since the oil was highly paraffinic, the precipitation of different organic components (paraffins, asphaltenes etc.) in both the reservoir and the surface facilities were uncertain. The interfacial aspects of this IOR/EOR technology were also obscure. The later questions stimulated the laboratory studies, and the results of the R&D activity are summarized below in this paper.

EXPERIMENTAL CONDITIONS

The laboratory studies, except the analytical measurements, were carried out under reservoir conditions using original formation oil (Alg-983) taken under pressure at well head. The basic properties of the live oil are listed in **Table 2**. The original oil has extremely low bulk phase and interfacial viscosity.

Table 2.

Properties of live oil

Density (oil)	0.728 g/cm^3 (63 API^o)	CO_2	0.51 mol %
Dist. residue	0.8304 g/cm^3	C_1	46.80 mol %
R_{SI}	711 m^3/m^3	C_2	8.09 mol %
R_{oi}	3.94 m^3/m^3	C_3	10.91 mol %
$C_3 - C_6$	34 %	i-C_4	4.26 mol %
Dist. residue	27.5 %	n-C_4	6.86 mol %
Asphaltene (oil)	0.87 %	i-C_5	3.71 mol %
Dist. residue	1.19 %	n-C_5	3.81 mol %
Resins (oil)	0.19 %	C_6	4.73 mol %
Dist. residue	0.69 %	C_{7+}	8.51 mol %

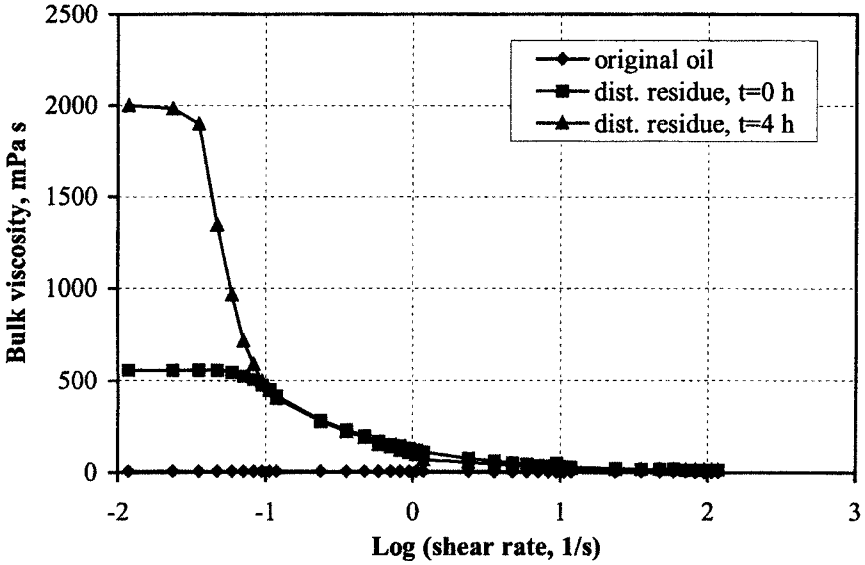

Fig. 1. Viscosity of oil and the distillation residue at different aging time

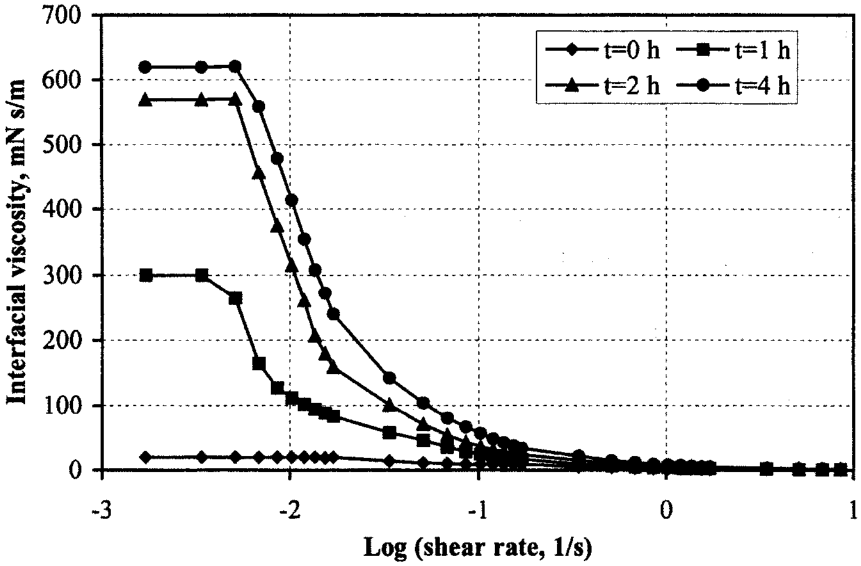

Fig. 2. Interfacial viscosity of oil/residue at different aging times

The distilled residue (cut above 210°C), however, shows not only extremely high viscosity, but also shear and time dependent features in both respects (**Figs 1** and **2**). In contrast to that fact, separating the light cut from the oil the interfacial tension of the residue scarcely differs from the original value (**Fig. 3**). As will be shown later, the radical modification of the rheological properties can be attributed to precipitation of solid paraffins from the homogeneous CH phase.

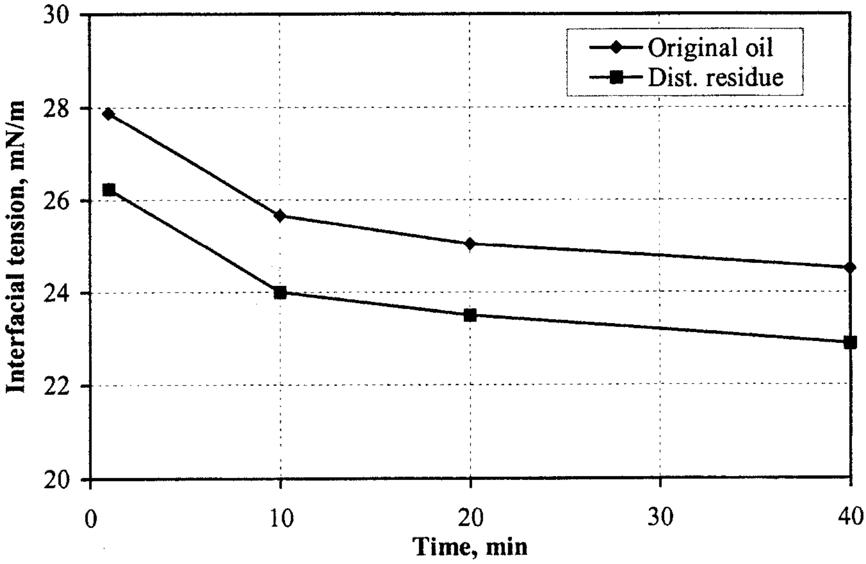

Fig. 3. Interfacial tension of the original oil and the distillation residue against water

The oil was contacted unsaturated CH_4, CO_2 and N_2 in batch reactor, dynamic rocking and shearing cells. The pressure and the temperature in the apparatus changed between wide limits (10–160 bar and 20–95 °C). The physical and chemical processes were followed by measurement of density, group composition and interfacial properties of homogeneous and dispersed samples taken in appropriate intervals from the cells.

Conventional and sophisticated methods were used for determination of the physical and chemical properties of oil and its fractions. The group analysis (asphaltene, resin etc. content) of oil was performed by standard separation techniques. The density was determined by a high pressure AP DMA 512/66 density meter, the molecular spectroscopic analysis was performed by Zeiss IR and UV-VIS photometers. The bulk phase and interfacial rheological properties were determined by Contraves Low Shear 30 rheometer. The surface and interfacial tension of oil/water systems were measured by the pendent drop method using computer aided digital image analysis. Similarly, the image analyzing apparatus was applied for determination of wettability.

RESULTS AND DISCUSSION

Effect of Vaporization on Oil Properties

The vaporization test was carried out with a simple distillation procedure. Prior to distillation the apparatus was flushed through by nitrogen. The samples were collected with 10 % vaporization steps. Since the predicted spontaneous vaporization under field condition is not higher than 50 %, the final loss in light fraction was 60 % at the end of the procedure. Although the distillates were also preserved, the residue, which lost the mentioned amount of light fraction, was then analyzed. The experimental results of vaporization test can be summarized as follows:

1. The density and the amount of group components (asphaltene, resin, etc.) of the residue is changing linearly with the degree of vaporization (**Figs 4** and **5**). These findings are in good agreement with the expectation and enrichment of the heavy components in the residue is in the background of the phenomena.
2. The interfacial tension of the oil/water systems is sharply decreasing in the initial period of vaporization, than above 30–40 % loss of light hydrocarbons the interfacial

tension set in equilibrium at about 15 mN/m, which corresponds to 25 % reduction of the original value (**Fig. 6**). That experimental observations imply that the natural surface active agents, originally present in a negligible concentration in the ultra light oil, are also gradually enriching in residue, but their effect on surface and interfacial tension is not proportional. Namely, after loss of 20–30 % light cut, the adsorption of amphipatic compounds at the interface is terminated reaching a saturated state or complete coverage.

3. The rheological properties of the distillation residues show the opposite change as a function of vaporization. In the initial period, up to about 20–30 % loss of light cut, the dynamic viscosity is practically constant. Above this limit, the change is measurable, while at 50 % vaporization a sharp and extreme increase in viscosity could be observed (**Fig. 7**). It is characteristic, that the rheological behavior of the bulk phase becomes extremely non-Newtonian. Similar behavior was also obtained for the interfacial viscosity.

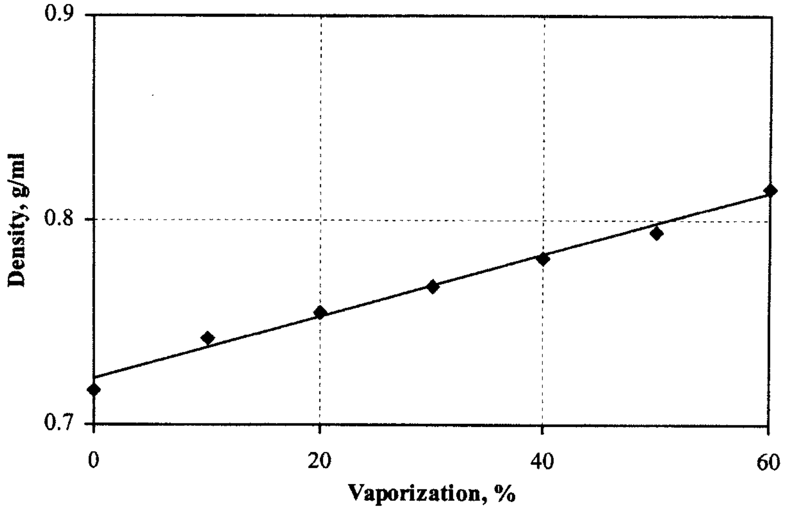

Fig. 4. Effect of vaporization on density of the residual oil

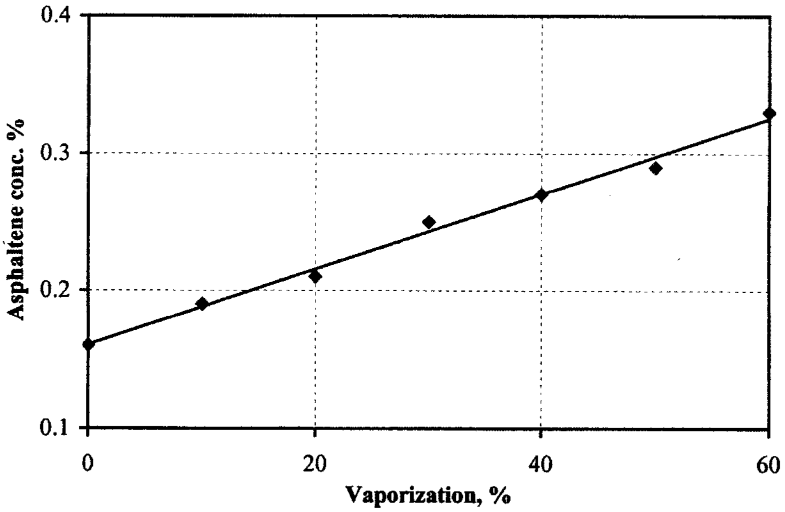

Fig. 5. Effect of vaporization on asphaltene content of the residual oil

4. Measurement of the film pressure at bulk water phase and calculation of the area per molecule and the compressibility modulus have definitely shown that both parameters changed according to a stepwise curve: the rigid molecules having small diameter the area occupied by a single molecule increased and the rigidity of the layer decreased with removal of the light fraction of oil, then it remained unchanged when the vaporization loss was between 20 and 40 %. Above this range, however, the presence of large molecules with rigid structure was predominant in the interface and therefore, the area per molecule and the incompressibility simultaneously increased (**Fig. 8**).

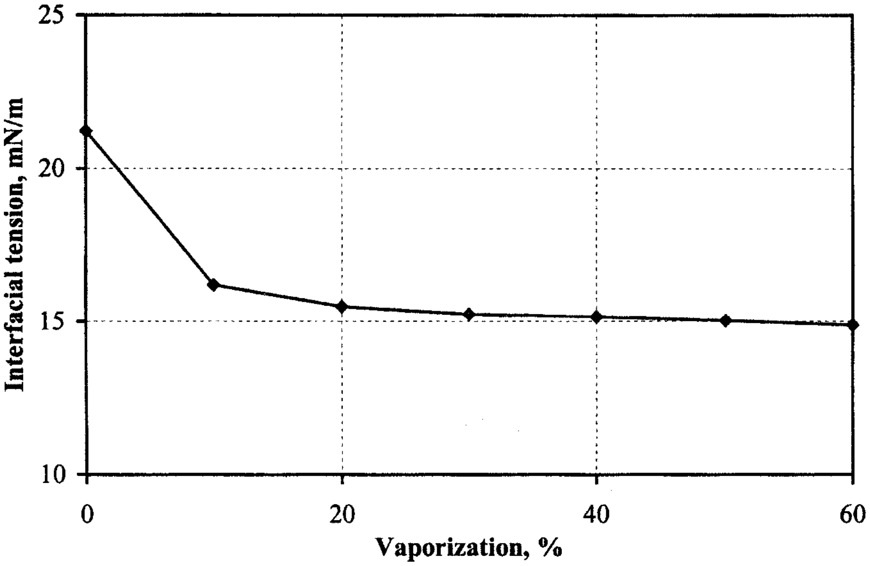

Fig. 6. Effect of vaporization on interfacial tension of the residual oil

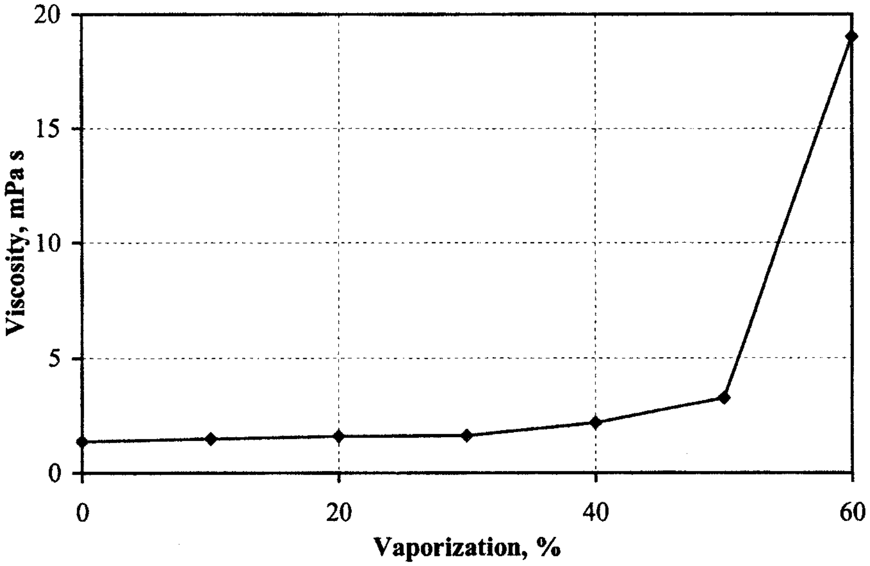

Fig. 7. Effect of vaporization on bulk phase viscosity of the residual oil

The experimental results can be explained by the following way. The loss of light hydrocarbons influences the rheological properties only in extent as it might be expected by enrichment of the heavy components if the liquid phase retains its homogeneous character. At high loss of light cut, however, the hydrocarbon phase becomes "bad" solvent for some components of the oil. As it might be visualized, the phase is already turbid after 50–60 % vaporization, which must be attributed to precipitation of solid paraffins. Since the paraffin crystals form a special internal network structure in solution, the non-Newtonian flow behavior and the extremely high bulk phase viscosity in the low shear rate range is quite reasonable.

Evaluating the results in respect to the displacement process it might be concluded that deteriorating effects (in-situ emulsification, mobility change, permeability reduction, change of capillary pressure, etc.) apparently do not ensue if the degree of vaporization is less than 30–40 %. At higher vaporization, however, because of in-situ transformation of the homogeneous oil phase to a dispersed, multiphase system, serious problems may arise. Further the lower the formation temperature, the greater the predictable modification in permeability, residual oil saturation, recovery factor, etc.

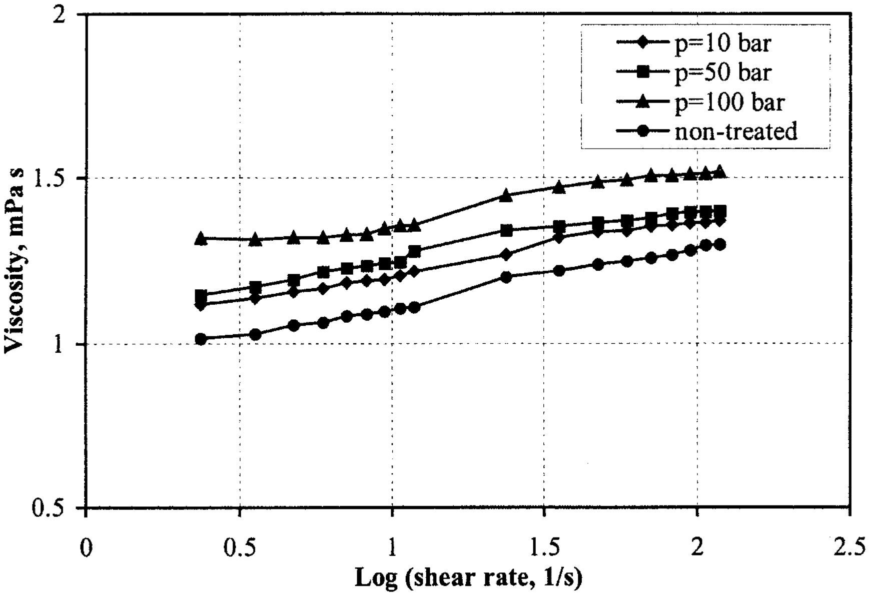

Fig. 8. Effect of vaporization on average area occupied by a single molecule and the compressibility modulus

Dynamic Test of Oil/Gas Systems

The dynamic test of oil/gas systems were carried out in a high pressure cell using the following experimental conditions:

Type of gases : CO_2, CH_4, N_2
Temperature : 95 °C
Treating time : max. 96 h
Volume of oil : 400 cm^3
Oil/gas ratio : 1:1
Pressure : 10–50–100 bar

The experimental observation obtained during the test can be summarized as follows:

1. Change of oil density and group composition suggests that approximately 10 % vaporization takes place during 4 days of the test. It should be pointed out, however, that both positive and negative deviation may occur from that value if the ratio of phases are different.

2. The type of gas and its pressure are not crucial in properties mentioned above despite their different solubility in the organic phase.

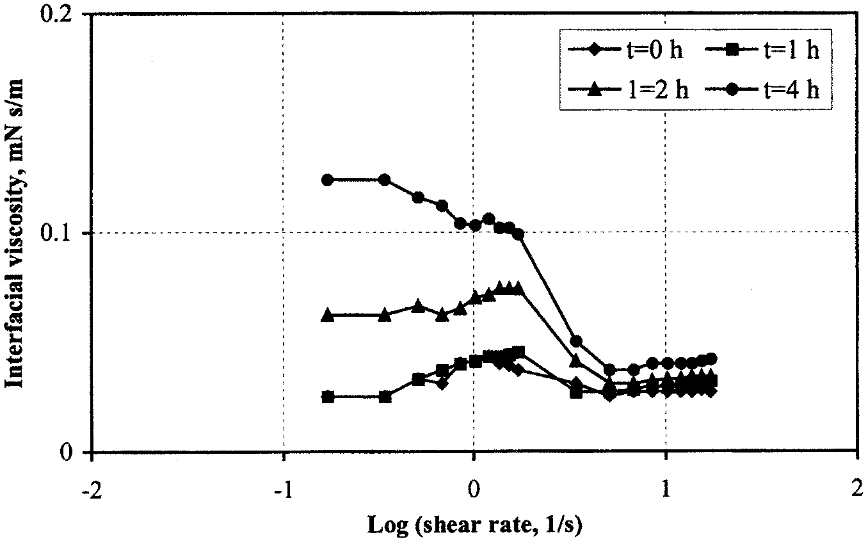

Fig. 9. Effect of nitrogen pressure on bulk phase viscosity of oil

3. The effect of pillow gas on bulk phase rheological properties is not uniform. The greatest viscosity enhancing effect was found for nitrogen. Although the change in the viscosities is relatively small (20–40 rel. % depending on shear rate, Fig. 9.), the effect of pressure is firm and pronounced. The phenomena can probably be explained by the fact that the nitrogen is the least soluble in the oil, viz. the vaporization loss is the highest under identical test conditions.
4. The effect of gas contact on interfacial rheological properties of the oil/water systems is more dominant. The interfacial viscosity increased in all cases. It is characteristic, however, that at high shear rate the effect is negligible, while in the low shear rate range or at "zero" shear rate it is extremely high. Indirectly, this proves the existence or formation of an inner network structure (intermolecular interaction) in the boundary layer (Figs 10–12). As shown on the relevant figures, the interfacial layers become not only highly viscous, but also non-Newtonian after relatively small evaporation loss. As far as the effect of gas quality is concerned, the following characteristics can be detected:

surprisingly, the effect is decreasing with the gas pressure, and

in general, the gases influence the interfacial rheological properties in sequence of $CH_4 \geq CO_2 > N_2$.

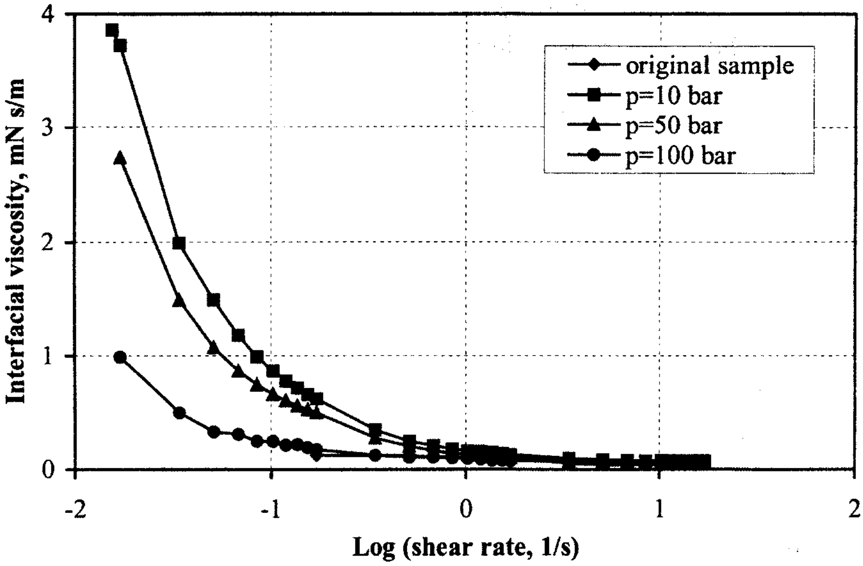

Fig. 10. Effect of methane on interfacial viscosity of oil/water system

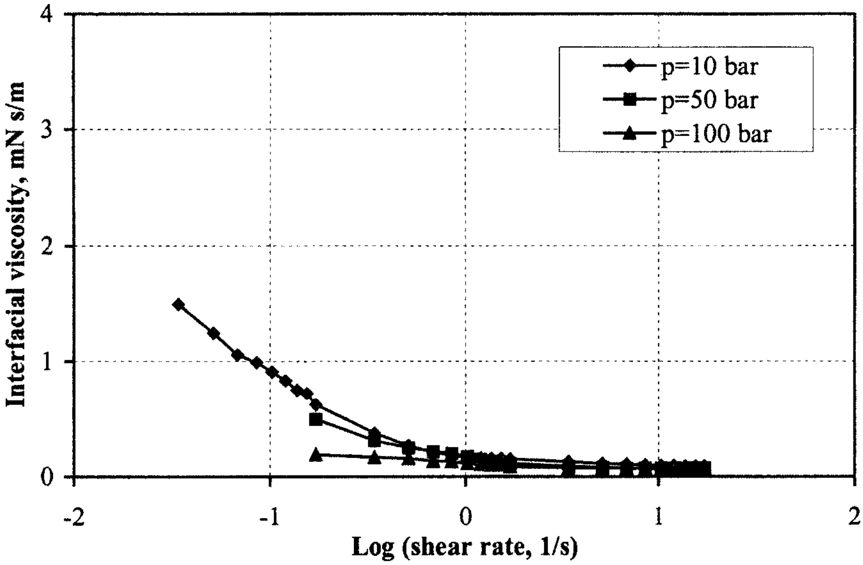

Fig. 11. Effect of nitrogen on interfacial rheological properties of oil/water systems

5. Since the absolute value of the interfacial viscosity is in the range where the standard deviation of measurement is already high, the stated sequence is not unambiguous in all tested cases. On the other hand, the definite effect of gas pressure suggests that the vaporization loss, as it might be expected theoretically, is gradually decreasing with the pressure.

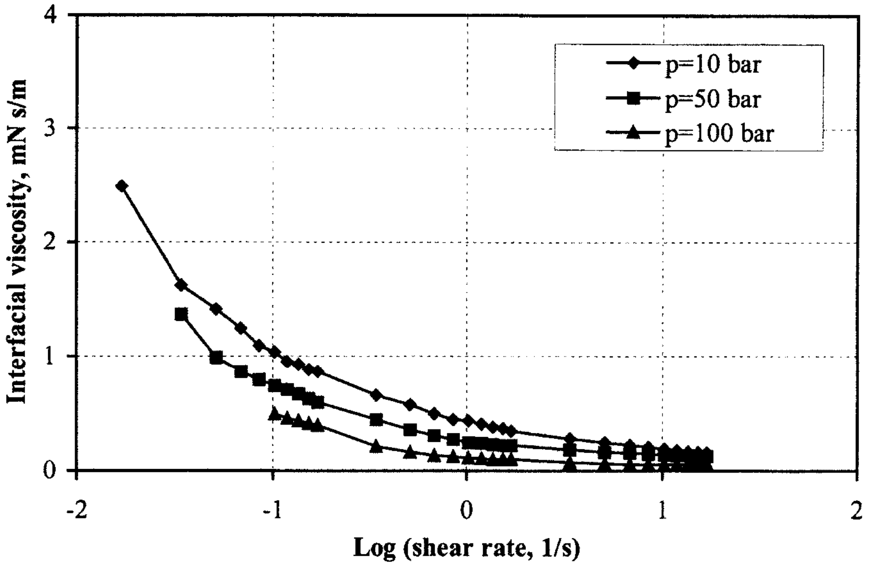

Fig. 12. Effect of CO_2 on interfacial rheological properties of oil/water systems

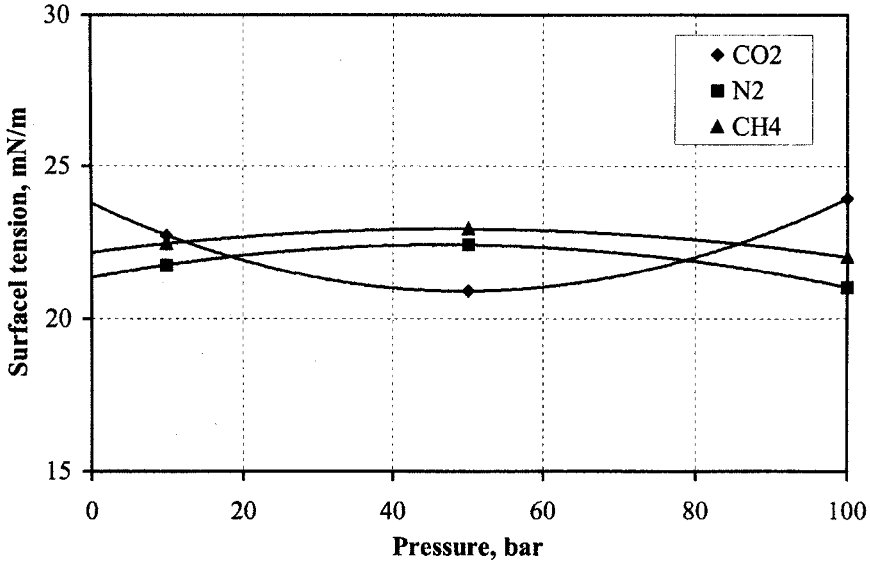

Fig. 13. Effect of gas pressure on surface tension of oil/air systems

6. In contrast to the interfacial rheological properties, the surface and interfacial tension of different systems are not influenced by neither the type of gas, nor its pressure. These observations can be explained so, that at low vaporization loss the lean CH and unsaturated inert gases have only tolerable effects on interfacial properties (**Figs 13–14**).

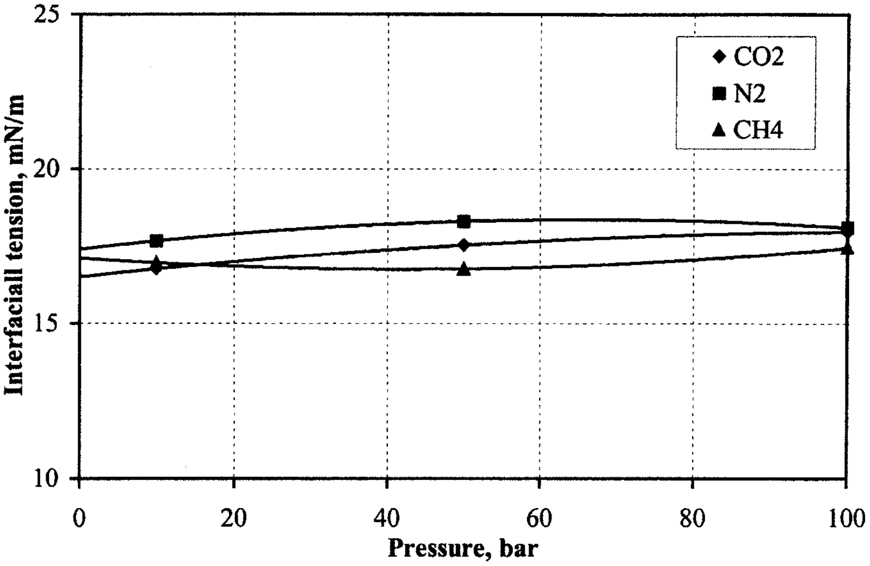

Fig. 14. Effect of gas pressure on interfacial tension of oil/water system

7. Converging results were obtained with the film pressure measurements. The area occupied by a single molecule in the interfacial layer and the compressibility modulus suggest a vaporization loss of 20–30 %. Practically, the same molecular size (~13 Å2/ molecule) were obtained independently of the gas pillow applied. In contrast to that findings the highest compressibility modulus (16 mN/m) could be calculated when CH4 was tested, while the lowest value characterized the layer in the case of N2. These latter results are in good agreement with those mentioned in paragraph 4).

The above mentioned conclusions were also proved by measurement of the acoustic wave propagation in the same samples. The apparent contradictions of the experimental results can be resolved by supposing that a catalyzed precipitation of paraffins and other constituents of the oil is taking place in the oil/water boundary layer. That process influences only the interfacial rheological properties and not the surface energies. According to the observations this may happen well before the precipitation in the bulk oil phase commences. Obviously, this new hypothesis needs further approval. On the other hand, if it is realistic, than we may get closer to the interpretation of some blur engineering problems often met in practice of oilfield operation (e.g. unexpected deterioration of productivity, precipitation of waxes, paraffins, asphaltenes and their mixtures at the bottom hole and the surface facilities).

Shearing Test of Oil/Gas and Oil/Water/Gas Systems

The shearing tests were carried out using a high speed gear pump and a HP nebulizer. The continuous shearing time was 4 days maintaining 5–10–15–20 bar pressure in the devices. The volume of oil was 1.5 dm^3 corresponding to 1:2 liquid/gas ratio. The results of the shearing tests may allow us to conclude the following:

1. On account of the greater liquid/gas ratio higher amount of light hydrocarbons (25–30 %)vaporized into the gas phase. Accordingly, the density and the group composition of oil changed more significantly than during dynamic tests.
2. After treatment the surface tension of the oil and the water remained the same before the test. The interfacial tension of the oil/water systems (14–16 mN/m) is, however, indicating also an enhanced vaporization effect.

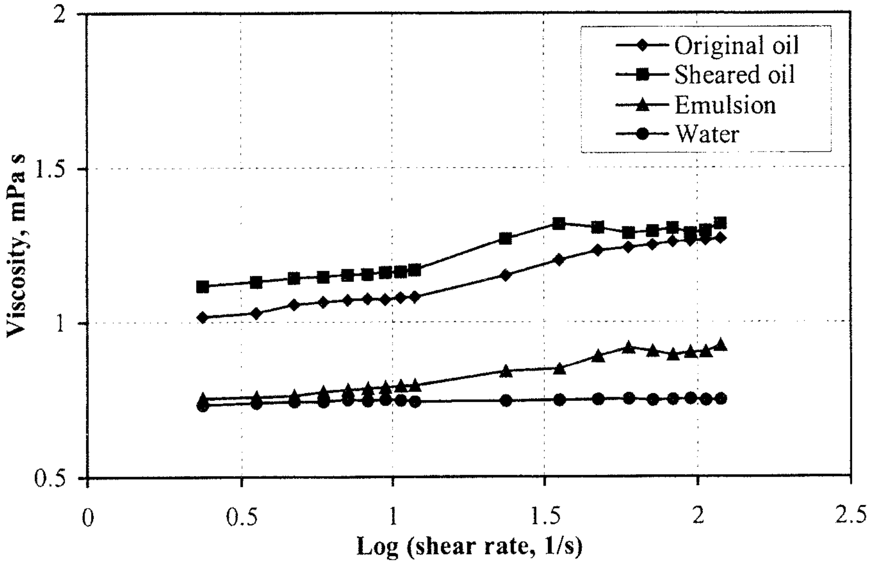

Fig. 15. Effect of shearing in methane on bulk viscosity of different phases

3. The phases separated quickly after treatment, but it was characteristic that the aqueous phase remained turbid even after weeks of treatment. The amount of the dispersed phase was extremely low, usually less than 1–2 %, and proved to be paraffin.
4. The rheological properties of bulk phases correspond to the expectations. Similar viscosity was measured for the aqueous phase before and after the treatment, while the viscosity difference between the original and the sheared oil samples is proportional with the loss of the light cut (Figs 15 and 16). The weak dilatancy of treated phases can be attributed to homogenization of the partially dispersed phases. Substantial mechano-chemical effect, which should be attributed to high shear rates and forces, was not detected in samples.

The results of the shearing test firmly support the earlier findings. It was further proved that when the vaporization proceeds, but remains below 50 %, the precipitation is predominant and limited only to the interfacial layer and not to the bulk oil phase. As a result, the enhanced interfacial paraffin precipitation may lead to formation of a dispersed aqueous phase, meanwhile the oil remains still homogeneous. Here, it must also be underlined that at low degree of vaporization and small interfacial surface area of phases, there is a little chance for formation of a stable paraffin/water dispersion because the system is paraffin deficient.

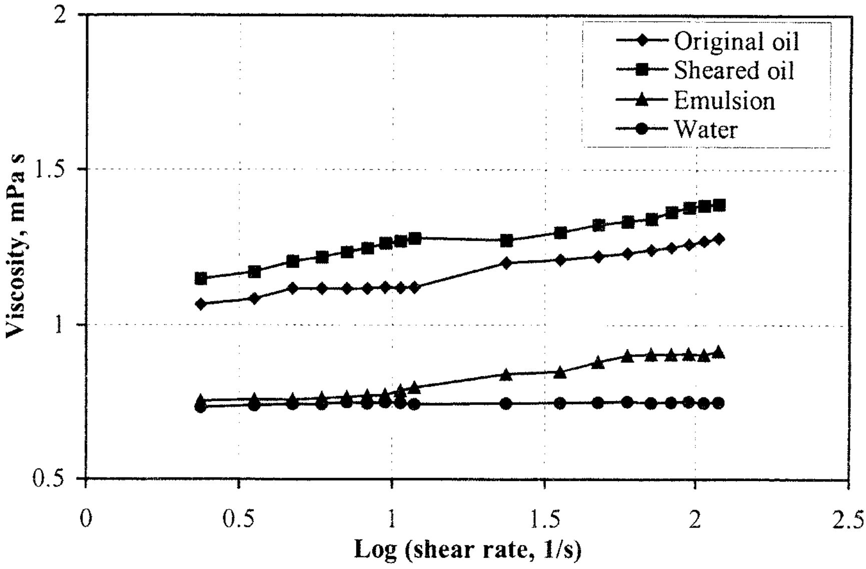

Fig. 16. Effect of shearing in nitrogen on bulk phase viscosity of different phases

After all, from reservoir engineering point of view, it may be concluded that the phenomena have negligible effect on displacement efficiency under reservoir conditions injecting lean gases into the systems if the vaporization loss is below 10–20 %. However, it must be emphasized that in the presence of water and above 30 % vaporization loss the multiphase system becomes unstable in respect to precipitation of paraffins. Consequently, precipitation of such compounds may occur both in-situ and in the surface facilities. Namely, the phenomena can be detrimental simultaneously for both the recovery process and the surface technology.

CONCLUSIONS

Detailed laboratory studies were carried out to determine the possible effect of lean CH and inert gases on interfacial properties of an oil/water/gas system. On the basis of the experimental findings obtained for an ultra light, paraffinic oil, the following conclusions were drawn:

1. The physical properties and the group composition of oil is changing proportionally with the vaporization of light hydrocarbons.
2. The vaporization, particularly in the initial period, caused some changes in the interfacial tension, but its extent may not be crucial to the displacement process and the emulsification of phases.
3. The bulk phase rheological properties of oil have shown sharp change over 50 % of vaporization, which could be attributed to accelerating precipitation of oil components, particularly paraffins.
4. The interfacial rheological properties show drastic modification even at low vaporization loss (< 10 %). This unique fact is explained by catalyzed interfacial precipitation of paraffins.
5. At high vaporization loss (20–40 %) the enhanced interfacial precipitation of paraffins may result in a formation of a paraffin/water dispersed system, meanwhile the appearance of a solid phase in the oil is still not detected.

From a reservoir engineering point of view, it may be concluded that the phenomena have negligible effect on displacement efficiency under reservoir conditions injecting lean gases into the systems if the vaporization loss is low. However, it must be emphasized that in the presence of water and above 30 % vaporization loss the multiphase system becomes unstable in respect to interfacial precipitation of paraffins. Consequently, precipitation of such compounds may occur both in-situ and in the surface facilities. Namely, the phenomena can be detrimental simultaneously for both the recovery process and the surface technology.

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