RESIDUAL OIL SATURATION AND MULTIPHASE RELATIVE PERMEABILITY MEASUREMENTS ON A WATER-WET SANDSTONE RESERVOIR AND A LIMESTONE RESERVOIR OF MIXED WETTABILITY

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ABSTRACT

This paper presents three phase data regarding a water-wet sandstone reservoir and a limestone reservoir of mixed wettability. These data originate from a laboratory method set up for a direct and comprehensive determination of tertiary recovery by gas injection, using both centrifuge and steady-state techniques.

The three-phase relative permeability determination experiments are performed using in situ saturation measurements by dual energy gamma-ray. The steady-state technique was used to derive water, oil and gas oil relative permeability isoperms at high oil saturations. Automated centrifuge tests were carried out to determine residual oil saturations resulting from both secondary and tertiary gas floods and oil and water three-phase relative permeabilities at high gas saturations.

The experiments show that residual oil saturations reach a very low value both in secondary and tertiary gas floods for the studied water-wet reservoir sandstone. It is also possible from reliable experimental three-phase oil relative permeability data to ascertain the choice of an analytical three-phase model for numerical modelization. In the case of the carbonate reservoir of mixed wettability, the residual oil saturations are not always as low as expected from secondary gas flood. Results indicate that permeability may be more important than wettability to influence the total recovery in the studied limestone reservoir.

The residual oil saturations and three-phase relative permeability data for a variety of wettability and permeability values reported in this paper are expected to provide the basis for added insight into tertiary gas injection phenomenology.

Introduction

Residual oil saturation and time required to reach it are key factors in designing tertiary gas injection recovery projects. The three phase oil relative permeability appears to be one of the crucial variables determining the kinetics of different improved oil recovery projects. Accurate predictions of oil recovery in processes that exhibit three-phase flow (Water, Oil and Gas) need rigorous model for three-phase relative permeability. Therefore, reliable acquisition data is essential for accurate prediction of oil recovery.

To warranty the choice of a three-phase relative permeability (kr) model for field scale simulation, a comprehensive laboratory program should require :

1) to perform automated centrifuge tests and multiphase relative permeability determination using the steady-state technique to derive respectively the three-phase kr at low gas saturation and high gas saturations ;
2) to carry out an appropriate set of samples gas injection experiments at reservoir conditions using in-situ gamma-ray saturation monitoring and analysed it using a numerical simulator as described by Chalier et al (1). By matching the profile saturations and fluids productions during gravity drainage, it will be possible to derive a three-phase model which have to be compared with ambient results. This final comparison will validate and confirm the choice of a three-phase kr model for full scale simulation.

The results obtained on two different reservoirs and related to ambient conditions experiments are reported in this paper. Experiments were carried on numerous small plugs (4 cm to 10 cm length, 4 cm diameter) at ambient conditions to describe all the encountered flow units in relation with the geological model.

Recovery mechanisms into the reservoir for lean gas injection project

During tertiary gas injection, additional oil is recovered as a result of several individual mechanisms mainly component exchanges and gravity drainage. At ambient laboratory conditions, only gravity dominated mechanisms will be considered. This is the case of lean gas injection at fairly low pressure where gas is injected continuously to replace the voidage. It should be noted that gravity drainage still acts in the gas invaded zone even if gas injection is stopped. The rate at which tertiary oil is draining will depend on the permeability of the rock, oil relative permeability and the oil viscosity.

Residual oil Saturations

Many laboratory experiments suggest that the process can lead to very low oil saturations. Dumore et al. (2) measured 3% residual oil saturation. There is also considerable field evidence (3) to show that in region containing gas, gravity drainage can be complete with residual oil saturations tending to zero. To be sure of mobilizing oil in tertiary conditions, experimental measurements are designed. These experiments have the objective to determine if additional oil could be recovered from different initial saturations : virgin area at Swi, waterflooded zone at Sorw or intermediate waterflooded zone. It is possible to compare and to evaluate the efficiency of gas injection for the different flow units by performing centrifuge experiments on samples representative of each unit. Displacing oil and water by centrifugal forces in a centrifuge make it possible to reach low liquid saturations, which is the region of interest in gravity drainage.

Relative Permeabilities

Relative permeabilities have to be measured at high gas saturations (around the secondary gas cap) and at low gas saturation (in the oil producers area). To cover the whole range of gas saturation, at ambient conditions, two different laboratory techniques were used : centrifuge technique for high gas saturations and steady-state technique for low gas saturations. As described by Oak et al (4) relative permeability is not a unique function of fluid saturation, but varies with the saturation history. In this study only one cas was considered, gas saturation is always increasing while the liquid saturation (water+oil) is decreasing.

Measurements techniques

The most important consideration in designing the experimental equipment was the reliability of the measurements.

Steady-state technique using gamma-ray in situ saturation monitoring

The steady-state method only requires establishment steady-flow of three fluids through the porous medium and measuring the pressure drop and flow rate for each fluid. To determine the relationship between relative permeability and saturation, necessary to measure the saturation of each fluid under steady-state conditions for each set of flow rates is measured using a dual energy gamma-ray attenuation technique bench. The in-situ saturation monitoring technique is similar to the one described by C. Barroux et al (5). Water, oil and gas are simultaneously injected into the sample at constant rates, and pressure and fluid phases are measured at steady-state. The three-phase test is conducted at gas-oil and water different flow rate ratios. One tried to increase the gas saturation continuously either by increasing the gas rate or by decreasing the total injection rate of water and oil at a constant water-oil injection ratio.

According to the experiment different couple of oil-water systems were used. Oil or brine may be recombined with dopant to enhance the constrast for gamma-ray readings. The synthetic formation brine corresponds to the reservoir formation water. To eliminate end-effects, the pressures are measured using transducers located at some distance from the plug ends.

The saturation history is operated as follows :

Initially, the core is clean and dry when set up horizontally in the Hassler core holder cell. The dry profile of the set up (i.e. Set-up + Core Assembly) is then determined precisely. After saturation of core with brine, the saturated profile is determined. The establishment of Swi is done by centrifugation or displacement. At this stage, profile at immobile water saturation can be compared to the material balance Swi.

The three-phase test is conducted at gas-oil and water different flow rate ratios. At the end of the flooding, the core is removed from the core holder to determine final water saturation. A flooding by isopropanol is used to extract the water from the core and a titration is done. This checking confirms the saturation readings by gammagraphy.

The centrifuge technique

This technique for measuring three-phase relative permeability is the systematic application of the centrifuge method described by Van Spronsen (6). Relative permeabilities are calculated from the observed desaturation rates at a given rotationnal speed. To ensure accurate fluids production data, centrifuged samples were of large dimensions (i e. utilisation of high capacity centrifuges) and the technique has been automatised using video camera.

Procedure of centrifuge technique

The procedure for preparing samples for a centrifuge experiment varied somewhat according to the rock wettability. However, the main procedure to establish the initial conditions is as follows. The samples are cleaned, dried and completely saturated with the water phase. Irreducible water saturation (Swi) is established either by displacing the water with oil in flood apparatus or by centrifuging in an oil filled core holder. If necessary, samples are ageing 20 days to restore the wettability. The establishment of intermediate saturations is done by waterflooding at very low flow rate. Another technique is to inject simultaneously at a constant high rate until a steady-state condition is reached. Subsequently, the samples are placed in air-filled core holder and three-phase relative permeability experiment is started. The initial and final sample saturations are checked by weighing before and after the centrifuge run.

Determination of triphasic end-points

The average oil saturation at a gas-oil capillary pressure have to be corrected using Forbes' method (8) to obtain the saturation at the end of the plug. It means that for each petrophysical rock group a representative gas-oil capillary pressure curve is determined by the centrifuge method. For triphasic end-points, samples have to be fully or partially waterflooded before centrifuging into air.

Determination of oil relative permeability in triphasic conditions

A three-phase relative permeability experiment entails running the centrifuge at a single high speed in an attempt to overwhelm capillary pressure effects. The conventional analysis of Hagoort (9) extented by Van Spronsen (6) assumes that first the centrifugal acceleration is constant along the core and second the invading phase is infinitely mobile compared to the phases it displaces. These assumptions can be reasonnably approached. The first assumption is satistified as soon as the distance between the rotational axis and the middle of the sample exceeds twice the sample length. This is accomplished by using high capacity centrifuges. The mobility assumption is certainly not valid in the beginning of the test when the gas is just entering the core,its saturation and, hence its permeability is low. But the high viscosity constrast insure the mobility assumption is valid throughout most of the experiment.

Experimental results

Here we give some examples of triphasic end-points and three-phase relative permeability measurements on samples from a water-wet reservoir and a limestone reservoir of mixed wettability. The case study of the water-wet reservoir was chosen to illustrate how from centrifuge and steady-state technique it is possible to define a reliable three-phase oil relative permeability model. Mixed wettability reservoir have much more complex flow behaviour. The chosen case shows that within relatively short time residual oil measurements in secondary and tertiary conditions bring an evaluation of the potential of gravity drainage for all the flow units of a limestone reservoir. A summary of the results together with the core properties is given in Tables 1&2. Another point worth noting is that, in centrifuge experiments residual water saturations (Swig) may be sometimes lower than Swi.

A water-wet sandstone reservoir

Samples were from an oil field that has nearly produced its secondary conventional reserves. The reservoir is a sandstone reservoir known as being water wet. Both steady-state and centrifuge mesurements were carried out which enables to cover the whole range of ternary diagram. As expected in a water-wet system, the water relative permeability is found to be the same function of water saturation in both the two-phase and drainage three-phase system. This was confirmed by the two different techniques at high gas saturations and low gas saturations. This will validate the consideration of the whole set of data (both steady-state and centrifuge) to calculate oil isoperms. This significant result is shown on Figure 1.

The saturation paths during centrifuge and steady-state experiments are shown in Figure 2 in a ternary diagram. The data interpretation in terms of oil isoperms involves two steps of analysis. First, "experimental" isoperms are determined by using a gridding method directly from the raw data. The algorithm is based on a classical inverse-distance, radial searching technique. In the second step, the curvature of the minimum oil saturation (Som) curve is set from the "experimental" isoperms. Then, an analytical tree-phase kr model is searched to fit the whole experimental data set by varying adjustable parameters of the Som curve. The fitting of Fayers (9) or modified Stone 1 (10) model enables us to have meaningful results for future modelization. "Experimental" and modified Stone 1 kro isoperms are reported respectively in Figure 3 and 4.

A limestone reservoir of mixed wettability

Samples were from a limestone reservoir which is currently producing under natural depletion with an active bottom water drive. The wettability of this limestone reservoir changes from water-wet low on structure near the water-oil contact to mixed-wet behavior up to oil-wet higher on structure. The effect of these wettability variations is clear on the water-oil forced imbibition capillary curve shape at low oil capillary pressure but hidden on the values of residual oil saturation (Sorw) which depends mainly on permeability.

Diphasic results (i.e. gas-oil capillary pressure at Swi and water-oil forced imbibition) make it possible to compare the efficiency of gas with that of water in secondary conditions. It shows as illustrated by Figure 5 that in all cases oil recovery is better by gas than by water for equivalent hydrocarbon column, except for very low heigths and samples with lower permeability.

Recovery by gas injection in secondary conditions is very high for high permeability samples, Sorg is low even at low capillary pressures.

In Figure 6 are reported the two correlations, Sorw with gas permeability and Sorg with gas permeability corresponding to the same hydrocarbon column (80m), and the results from triphasic end-points experiment on the same samples.

Differences are identified from secondary to tertiary conditions. Tertiary end-points Sorgw are on the whole located between Sorg and Sorw. This means that gas injection is better in secondary conditions than in tertiary conditions. The wettability may be an explanation. After waterflooding, gas did not have access to the oil present in small pores or on the pore walls of larger pores.

Discussion

Centrifuge and steady-state experiments as described above were designed to acquire maximum reliable data in a relatively short time. Because of the assumptions taken for data interpretation, this method is preferably applied to permeable reservoirs. The two techniques can also be used for three-phase relative permeability measurements on low permeability samples if a numerical correction procedure is applied to take into account the error due to capillary end-effect.

It should be reminded that no mass transfer between oil and gas is involved in these experiments. Under certain conditions depending on gas and reservoir oil composition and reservoir pressure, high microscopic displacement efficiency may be achieved by thermodynamical dominated mechanisms that can be estimated only by additional reservoir conditions experiment.

The main feature of the method is to combine two different experiments to have fully coverage of ternary diagram from high to low gas saturations at ambient conditions. Unless the whole set of tests is performed on the same sample, which is actually unpractical, some scattering occurs in three-phase data. But in this water wet reservoir case study it was possible to ascertain a Fayers (9) or a modified Stone I model (10) from the experimental oil isoperms. Since the fitting between the estimated values and the measured ones are based on the Som curvature, the best fitting of kro is obviously obtained for low oil saturation region.

In a mixed wettability system, Stone (10) conjectured that the respective oil and water equations may be used in the different saturation ranges where they are applicable. Thus, for example, oil permeability may be computed at the lower ranges depending on the distribution of wettability according to pore sizes, thus on the rock. In that case, no three-phase model is directly applicable without fitting some experimental data, enhancing the need of a methodology such as that reported. It is hoped that it will also be validated by the additional data, in terms of three-phase kr, being currently determined on the limestone reservoir although the wettability aspect implies more difficult acquisition.

Conclusions

① Combining in situ-saturation monitoring steady-state and centrifuge experiments is an efficient method for measuring water and oil relative permeability and residual oil saturations in triphasic conditions.

② Reservoir characterization is as crucial as flow mechanisms modelling for gas injection projects. Steady-state and centrifuge advanced techniques run at ambient conditions make it possible to describe in relatively short time, the whole studied reservoir.

③ For a water-wet reservoir, it is possible to identify a reliable three-phase model from laboratory experimental data.

④ The efficiency of gravity drainage mechanism as an oil recovery process may be less in tertiary conditions than in secondary conditions for a limestone reservoir of mixed wettability.

Nomenclature

Kg	Gas permeability
Krg	Relative permeability to gas
Krw	Relative permeability to water
Kro	Relative permeability to oil
Keo	Effective oil permeability
Kw	Brine permeability at Sw=1.0
Pc	Capillary pressure
PV	Pore volume
Sg	Gas saturation
So	Oil saturation
Soi	Initial oil saturation before gas displacement
Sorg	Residual oil saturation to gas
Sorw	Residual oil saturation to water
Sorwg	Three phase residual oil saturation
Sw	Water saturation
Swi	Irreducible water saturation
Swig	Final immobile water saturation
μ	Viscosity

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TABLE 1 - Water-wet sandstone reservoir - Centrifuge and steady-state relative permeability tests

Experiment	H5	H3	H5b	H3B	H6	H7	H3C	c8	c9	c2B	c2b
Type	Steady-state							Centrifuge			
Qw/Qo or acceleration,g	1 / 5	1 / 1	10 / 1	20 / 1	Qw=0	Qg=0	Qw=0	3513	3515	3608	321
Sample Properties											
Sample length, cm	7.8	7.8	7.7	6.8	7.9	8.0	6.2	4.3	4.3	3.9	3.9
Sample diameter, cm	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Porosity, per cent	25.5	21.1	28.2	28.1	27.1	26.7	28.3	27.7	27.4	27.0	27.1
Swi, per cent pore space	19.0	17.0	20.3	23.5	23.2	23.1	23.9	19.1	17.9	21.5	20.8
keo at Swi, mD	463	456	556	401	386	484	420	758	752	278	280
Tests End-Points											
Soi, per cent pore space	46.6	52.3	70.6	66.5	-	76.9	-	22.8	49.3	39.7	30.0
Swig , per cent pore space	-	-	-	-	-	-	-	13.8	15.3	10.8	22.1
Sorwg, per cent pore space	-	-	-	-	-	-	-	**6.0**	**6.4**	**8.6**	**13.3**

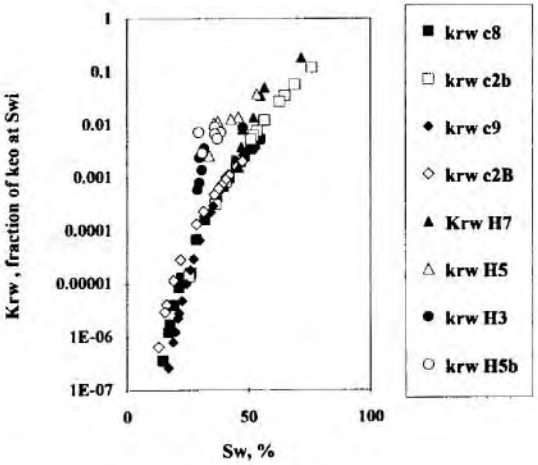

Figure 1. Water-wet Sandstone Reservoir. Water Relatrive Permeability as a Function of Sw.

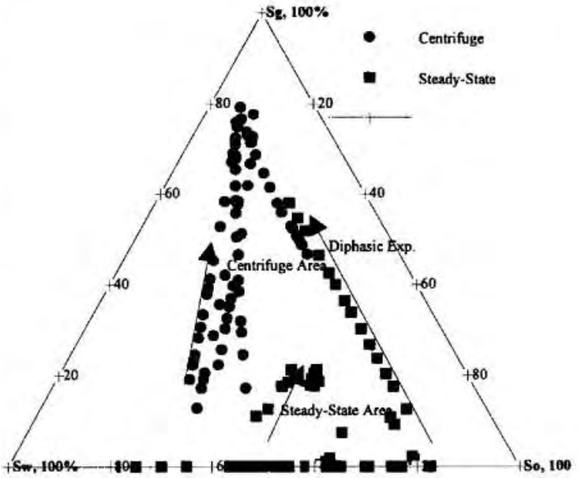

Figure 2. Water-wet Sandstone Reservoir. Saturation Paths of Centrifuge and Steady-State Experiments. Arrows : Direction of Saturation change

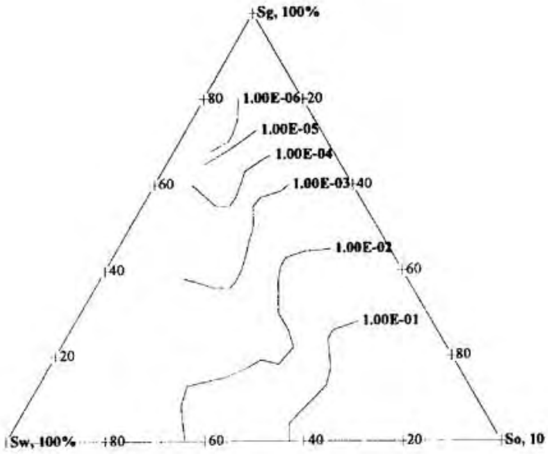

Figure 3. Water-wet Sandstone Reservoir. Experimental Oil Isoperms Estimated by Gridding Techniques from Raw Data.

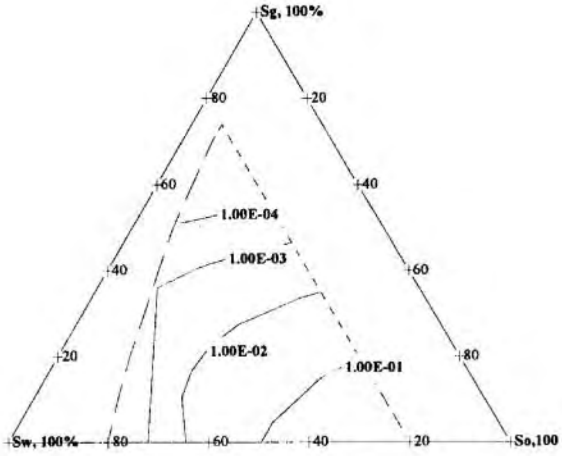

Figure 4. Water-wet Sandstone Reservoir. Analytical Oil Isoperms Estimated by Modified Stone 1 Method.

TABLE 2 - Limestone reservoir of mixed wettability - End-points in tertiary conditions

Sample Properties											
Well number	#1	#1	#1	#1	#1	#2	#2	#2	#2	#2	#2
Sample number	10	11	14	9	13	15	9	11	13	21	18
Porosity, per cent	24.8	26.1	20.8	22.7	16.7	25.7	25.1	25.1	23.8	15.0	17.7
Kg, mD	309	551	1188	99.2	317	21.3	38.5	12.2	90.2	5.17	3.34
Swi establishment											
Swi, per cent pore space	19.2	21.1	27.0	21.8	33.4	25.3	29.8	22.8	34.6	15.2	13.8
keo at Swi, mD	127	193	877	26.6	134	11.1	14.3	8.79	47.7	0.97	1.59
Intermediate saturation before gas displacement											
Soi, per cent pore space	**37.4**	**35.9**	**24.1**	**40.8**	**33.3**	**38.6**	**45.4**	**41.3**	**37.9**	**39.0**	**38.1**
After gas displacement of oil and water at a constant capillary pressure											
Swig , per cent pore space	29.8	28.7	41.0	25.7	29.7	21.5	21.0	15.7	21.2	18.6	20.8
Sorwg, per cent pore space	**17.2**	**15.7**	**8.3**	**21.2**	**16.7**	**19.3**	**22.2**	**29.9**	**18.8**	**38.2**	**37.8**

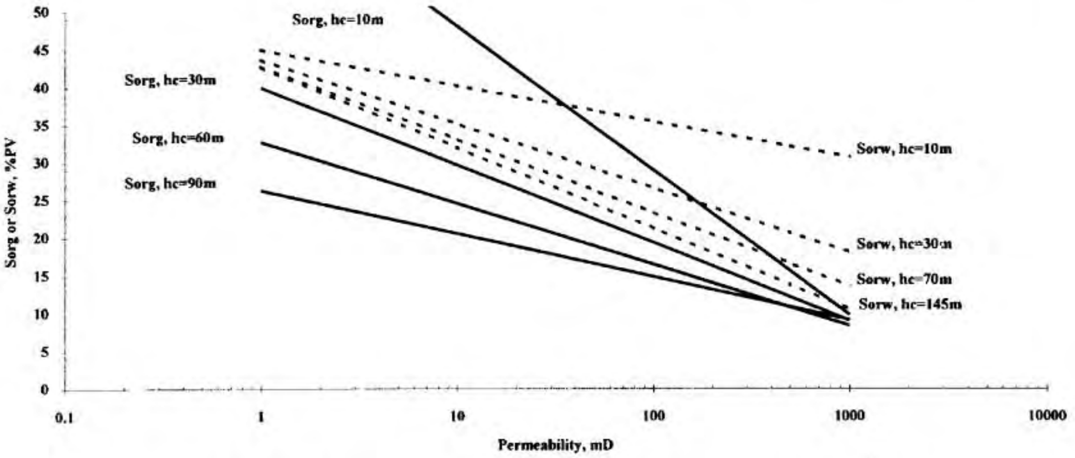

Figure 5. Limestone Reservoir of Mixed Wettability - Comparison between Oil Residual Saturation to Gas and to water Displacement. Equivalent Hydrocarbon Column, hc.

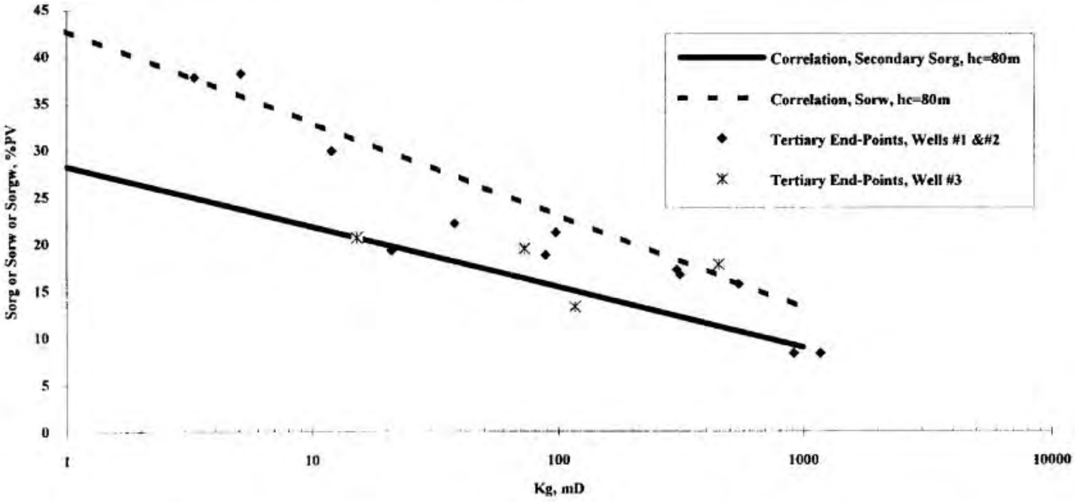

Figure 6. Limestone Reservoir of Mixed Wettability - Comparison between Oil Residual Saturation after Gas Displacement in Secondary and Tertiary Conditions.