Effect of trapped gas saturation on oil recovery during the application of secondary recovery methods in exploitation of petroleum reservoirs

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REVIEW

The paper presents the effect of trapped gas during the application of secondary processes, or more precisely, in the period of application of conventional waterflooding of partially depleted oil reservoirs. These processes can be simulated by analogous tests on reservoir rock samples, on synthetic models under laboratory conditions or by numerical models. An explanation of physical mechanisms that take place during such processes is required to understand better the benefits of gas phase saturation, and additionally to that, favourable and unfavourable factors present during such processes are explained. Besides, here are as well explained procedures for finding optimal trapped gas saturation, by which, for the selected partially depleted reservoir and the selected combination of fluids, and by waterflooding with maintenance of a nearly constant reservoir pressure, maximal ultimate recovery is achieved. At the same time, it is a guideline that waterflooding should start when, during the natural process of recovery by solution gas drive, mentioned optimal gas saturation is accomplished. Finally, the paper gives a short review of the results of different simulation studies of such processes in which, inter alia, three-phase relative permeability curves with expressed effects of hysteresis are used.

Key words: maximal recovery, optimal saturation, trapped gas, waterflooding

1. INTRODUCTION

In petroleum reservoirs with dissolved gas drive the pressure decreases due to depletion and the resulting consequence is liberation of progressively higher quantities of gas from oil, i.e. production is carried out with increasingly higher gas-oil ratios. If the method of reservoir pressure maintenance by flooding is applied to such reservoirs, the gas present in the pore space has a certain influence on the quantity of oil remaining in the reservoir after the completion of that process, as well as on the final oil recovery.

In such processes for macroscopic study of displacement efficiency, the most often is used linear flow model. In simplified calculations, it implies the application of Buckley-Leverett's model of frontal displacement, whilst in more complex calculations one or multidimensional numerical models can be used.

Deviations from the linear flow model occur during the initial period of flooding, when the fluid flow is radial, and remains such until the moment when the banks of neighbouring wells connect into a joined bank. Naturally, it refers to the line injection-production well pattern, when assembling of individual waterflooding banks of neighbouring injection wells hereafter implies linear flow.

Reservoirs with large gas caps are generally poor candidates for waterflooding due to the possibility of water bank to bypass the oil through the gas cap area, and because of the risk that oil might be, by waterflooding, injected into the gas cap area, where it would remain trapped.

2. DESCRIPTION OF WATERFLOODING PROCESSES WITH THE PRESENCE OF TRAPPED GAS

Many professional papers and books in considerable detail describe the physical characteristics of the waterflooding processes with the presence of trapped gas.[1,3,7,11,12,13] In many cases it has been confirmed that the presence of free gas phase during waterflooding leads to lower residual oil saturation than during waterflooding with no-gas presence. It also applies to the natural water drive process, but due to the characteristics of such drive to maintain the pressure to a lesser or higher degree, it is simultaneously accompanied by liberation of only small volumes of gas from oil, which may also have a favourable impact. Additionally, if the average reservoir pressure is higher than the saturation pressure, gas is liberated only locally and in even smaller quantities.

2.1. Macroscopic aspects of waterflooding processes

The favourable effect of free gas during the waterflooding processes arises from the forming of immobile i.e. trapped gas saturation in the waterflooding bank area. If continuous gas phase is present in the reservoir prior to

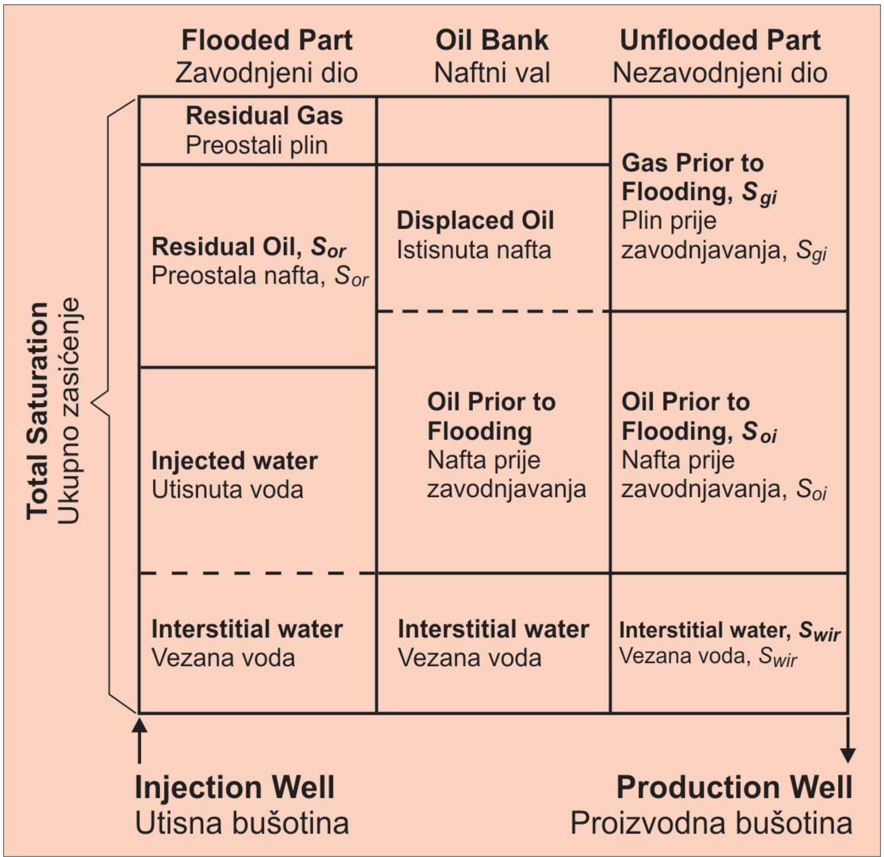

Fig. 1. Schematic presentation of areas saturated with different fluids between production and injection wells under conditions of displacement with immiscible fluid

Sl. 1. Shematski prikaz područja zasićenih različitim fluidima između proizvodnih i utisnih bušotina u uvjetima istiskivanja s nemješljivim fluidom

the advance of oil bank, during waterflooding a part of gas is forced forward by the oil bank and a part remains trapped within it. Fig. 1 schematically presents distribution of saturation in such a process, while Fig. 2 illustrates its simplified linear model.

In such processes reservoir pressure mostly remains constant, insomuch effects of gas compressibility and gas solubility in oil may be disregarded.

The results of core tests performed under laboratory conditions can be taken as confirmation of the above stated.[7] Fig. 3 shows oil and gas saturation profiles depending on cumulative injected quantity of water. The test was run on the core with initial mobile gas saturation. Only free gas was produced at the beginning of flooding. Afterwards production of gas ceased completely and oil without gas flowed at the outlet from the core (marked by O-O' line). It was to be expected due to the favourable oil-gas system mobility ratios (M = 0,1),[13] and because displaced gas always plays a role of non-wettable fluid.[7] After the water breakthrough (marked by W-W' line) oil continues to be produced, but with significantly higher water ratio in total fluid, until the completion of waterflooding test.

Fig. 3, and description of the test referring to that figure, indicate that

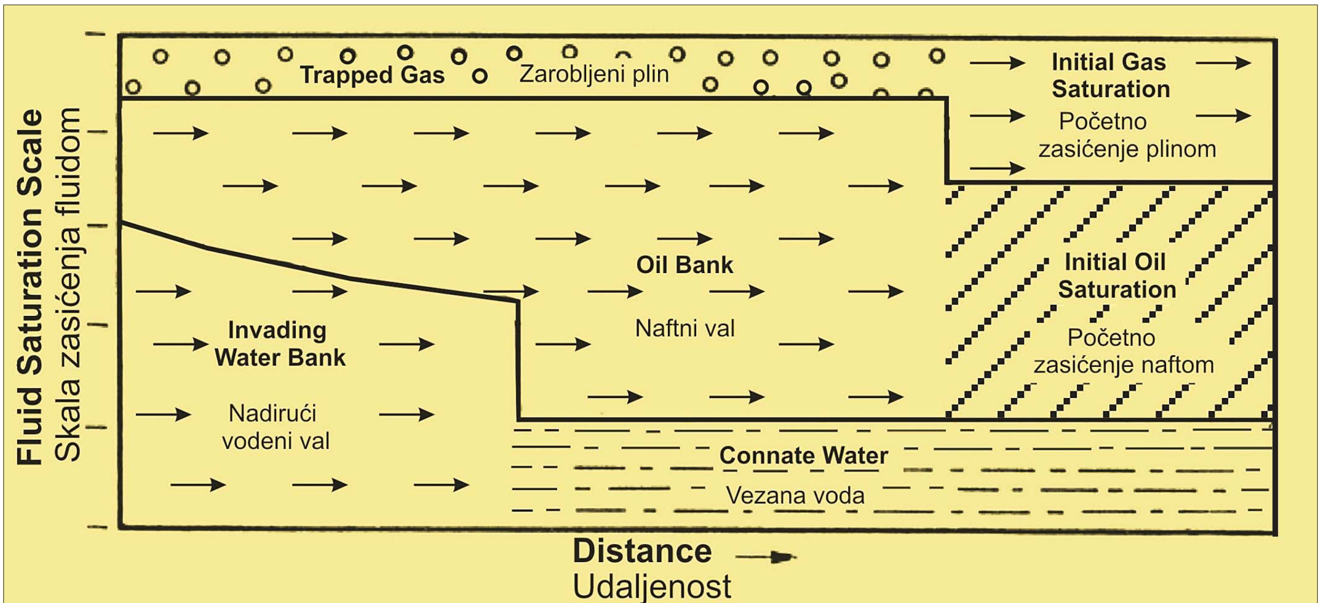

Fig. 2. Saturation profile that shows displacement of oil during initial saturation with mobile gas

Sl. 2. Profil zasićenja koji prikazuje istiskivanje nafte u prisutnosti početnog zasićenja pokretnim plinom

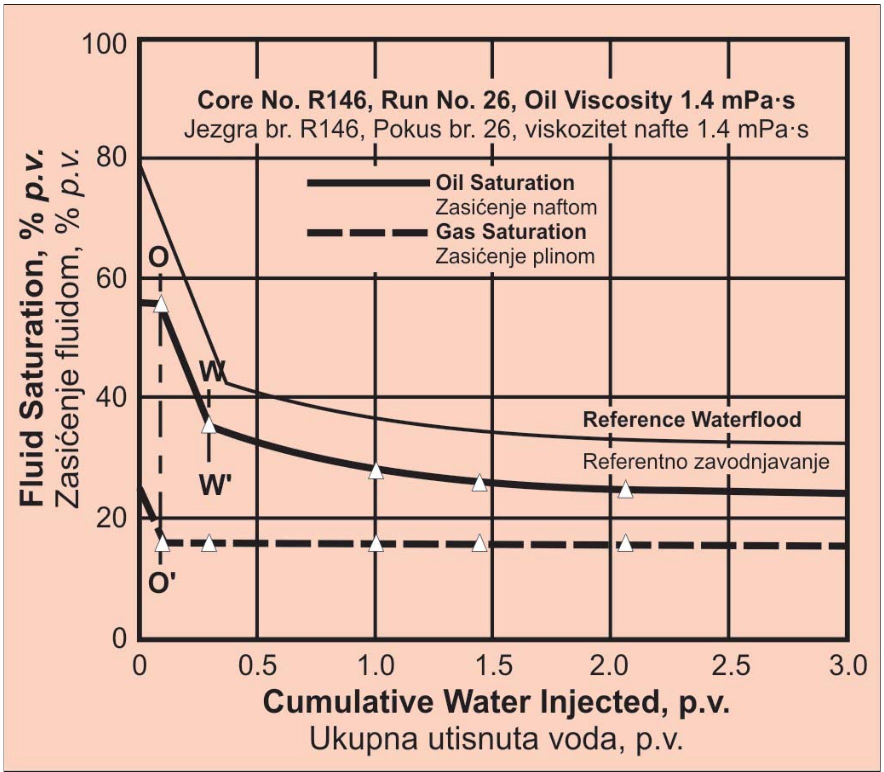

Fig. 3. Waterflooding in the presence of initial mobile gas saturation[7]
Sl. 3. Zavodnjavanje u prisutnosti početnog zasićenja pokretnim plinom[7]

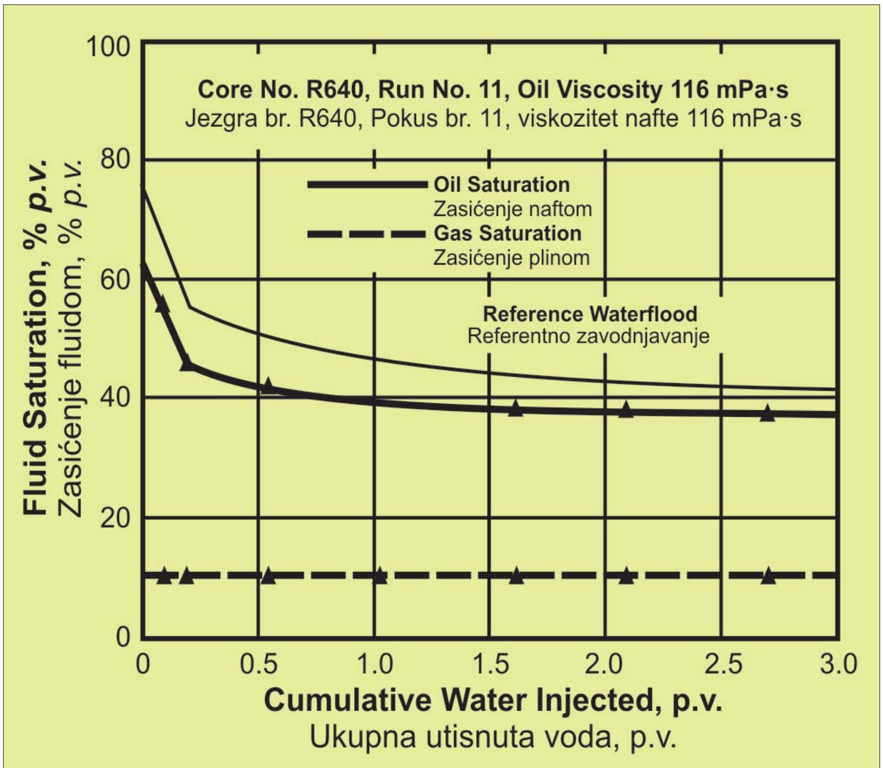

Fig. 4. Waterflooding when only trapped gas is present [7]
Sl. 4. Zavodnjavanje u prisutnosti zarobljenog plina [7]

two different banks are formed during such process, firstly an oil bank, followed by water bank. These two banks jointly advance through the core sample during water injection at the inlet core end, and it is in the form of saturation profiles illustrated in the same figure.

Fig. 4 shows the result of a test, where at the beginning of waterflooding the core sample is, additionally to oil, saturated only with trapped gas. It is evident from the figure that gas saturation of the core remains constant during the whole test and that only oil is produced at the beginning, followed by oil and water with gradual increasing of water-oil ratio in the total liquid. Thereby, waterflooding in the presence of trapped gas is actually analogous to the two-phase water-oil displacement that occurs in the part of the pore space unsaturated by gas phase.[7]

The curves of referent waterflooding in Figs. 3 and 4 (thinner lines) pertain to waterflooding tests without gas phase saturation of the core. The difference in oil saturations when gas is not, or is present (thicker lines), points to the favourable effect of gas during water injection in a sense of higher decrease of residual oil saturation at all times during the test duration.

2.2. Microscopic aspects of waterflooding processes

The trapped gas as non-wettable phase occurs in the reservoir as discontinued, in the form of mutually separate globules or discontinuous filaments.[3] Within the oil bank and ahead of the water bank, oil fills the pore space around trapped gas, except in the part of the reservoir which is saturated with connate water. In the water wettable system which contains oil, water and gas, it is to be expected that gas will be trapped in oil. It is a minimum total free surface energy position, as interfacial tension between gas and oil is lower than interfacial tension between gas and water.[3] Fig. 5 schematically shows positions of oil and gas in intergranular space at residual oil saturation.[3]

In the previous subchapter, the explained phenomena refer to water-wettable rocks, i.e. to tests on water-wettable reservoir rock sam-

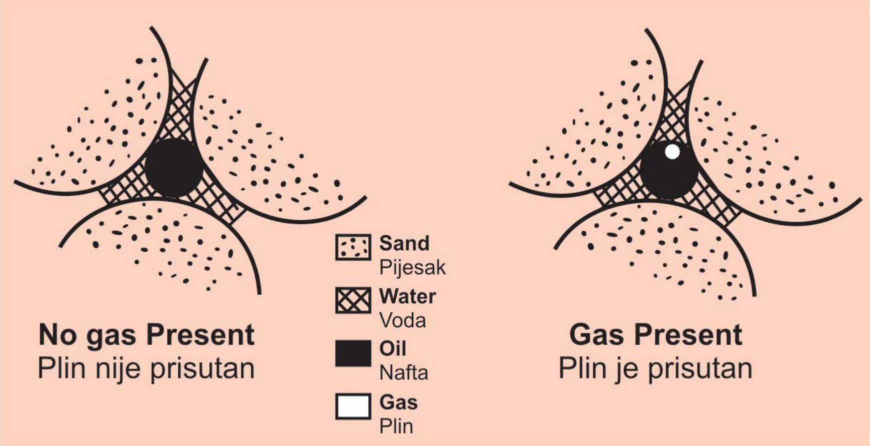

Fig. 5. The concept of oil and gas position in the pore space at residual oil saturation (water wettable systems)[3]

Sl. 5. Koncept položaja nafte i plina u pornom prostoru kod preostalog zasićenja naftom (vodomočivi sistemi)[3]

ples. Tests run on oil-wettable samples show that presence of trapped gas has no effect on final residual oil saturation. Explanation why trapped gas reduces residual oil saturation in water-wettable samples, but does not reduce it in oil-wettable ones, is as follows:

- In water-wettable rock the final residual oil saturation is trapped by water and residual gas is trapped within oil, thus occupying a part of pore space which would otherwise be saturated with additional residual oil.
- In oil-wettable rock the final residual oil saturation is in contact with the rock surface, and residual saturation with gas occupies the space which would be otherwise occupied with water.

With regard to water-wettable reservoir system, decrease of residual oil saturation due to saturation with trapped gas is the most beneficial effect during the waterflooding process for increase of ultimate recovery. Because of that, this subchapter is mostly dedicated to the description and explanation of such effect. Other, sometimes unfavourable effects present during these processes, are briefly described in further text.

3. ADDITIONAL FACTORS AFFECTING RESERVOIR WATERFLOODING PROCESSES WITH THE PRESENCE OF TRAPPED GAS

In addition to the main effect, previously described decrease of residual oil saturation, there are a number of other factors which in a lesser or greater degree, favourably or unfavourably, affect the waterflooding processes in the presence of trapped gas. Some of the more important ones are listed below:

1. Oil viscosity: the greater the oil viscosity, the less trapped gas it contains.[7,12] However, efficiency of trapped gas saturation is the highest in waterflooding of viscous oils.[7]
2. Increase of reservoir pressure: it is an unfavourable effect if we take into consideration the loss of trapped gas. If the oil bank is of greater thickness, it requires a higher displacement pressure, which causes gas compression and dissolution of gas in oil. Decrease of trapped gas in places where oil bank changes into water bank is accompanied by increase of residual oil saturation and simultaneous decrease of ultimate recovery. In other words, the process is in a lesser or greater extent changed into two-phase waterflooding - without gas presence. Besides, advance of oil bank to production wells is delayed for a quantity of oil which, due to the pressure increase in the reservoir during flooding, occupies the pore space previously saturated with gas.[13] Increase of reservoir pressure at the same time represents a favourable effect, since dissolving of gas trapped in oil causes its swelling and reduction of viscosity.[7] Oil swelling reduces its residual saturation, while reduction of viscosity leads to more favourable oil and water mobility ratio. Therefore, if we plan to utilize the effect of trapped gas during waterflooding, then the process should take place at pressure gradient that is very low, compared to absolute pressure in the whole system.
3. Decrease of relative permeability to oil: it is an unfavourable effect caused by the presence of trapped gas, which consequently leads to earlier water breakthrough. However, this effect is smaller than the favourable effect of residual oil saturation decrease, explained in the previous chapter. Fig. 6 shows an example of relative permeability to oil decrease due to gas presence.
4. Rock consolidation: in well-consolidated water-wettable rocks the effect of trapped gas saturation on residual oil saturation is significantly higher in comparison with unconsolidated rocks.[13]
5. Speed of running waterflooding process: at higher speeds, due to higher pressure gradient, gas dissolves in oil and the process turns into a two-phase waterflooding, and gas saturation effect is missing.[2] Because of that, at all cumulative injected water quantities, average oil saturation remaining in the reservoir increases with the increase of displacement rates. In other words, at all cumulative injected water quantities, oil recovery is the highest at the lowest displacement rates.[2]
6. Gravitational effects during waterflooding have an unfavourable effect: introduction of gravitational effect in calculation of waterflooding with the presence of gas causes markedly different performance from that of the one-dimensional horizontal systems. It is due to non-uniform vertical distribution of initial gas saturation and gravity effects on the injected water distribution.[2] Gravitational effects are related to the rate of process

running, reservoir thickness, physical characteristics of the reservoir's and injected fluids (solubility, viscosity and compressibility), relative permeabilities and areal waterflooding pattern (allocation of production and injection wells).[2] When we consider gravitational effects, lower waterflooding rates over a certain range result in lower oil recovery rates. Any horizontal reservoir has an optimal waterflooding rate due to opposing effects of gravitational influence and initial free gas saturation.[2]

7. Spreading coefficient: if positive, it has a favourable effect. Although in the paper which describes this coefficient[10] tests are run in reverse order from the processes that have to be dealt with in this paper (double drainage mechanism: injection of gas in strictly water-wettable media, saturated with water and residual oil), the effect of that coefficient can also be reviewed here. Spreading coefficient is represented by the following equation:

$$S_{ow} = \sigma_{wg} - \sigma_{og} - \sigma_{ow} \quad (1)$$

where:

S_{ow} = oil/water spreading coefficient, dyne/cm
σ_{wg} = interfacial tension of water/gas system, dyne/cm
σ_{og} = interfacial tension of oil/gas system, dyne/cm
σ_{ow} = interfacial tension of oil/water system, dyne/cm

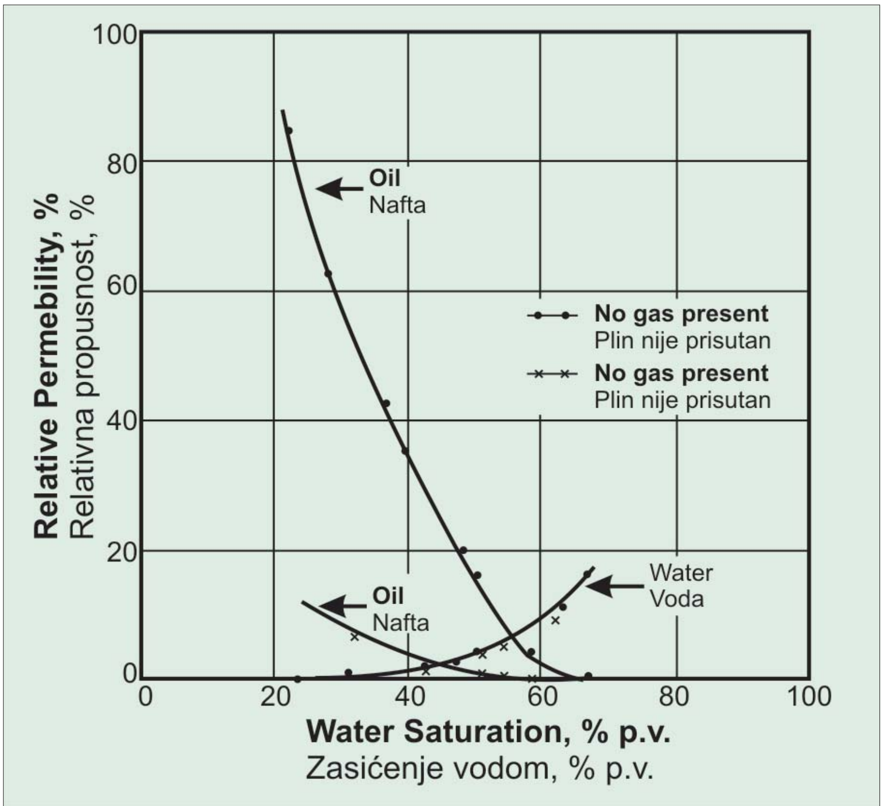

Fig. 6. Relative permeability to oil and water for the two systems in the Nellie Bly sandstone[3]
Sl. 6. Relativna propusnost za naftu i vodu za dva sistema u Nellie Bly pješčenjaku[3]

If that coefficient is positive, oil tends to form a continuous film between water and gas. If the film is thick enough, oil flows through that film, reducing its residual saturation. If the coefficient is negative, the oil film breaks, and so does the flow through it. Tests have shown that in cases of positive spreading coefficients, markedly higher recoveries were accomplished than in case of negative ones.

4. OPTIMAL GAS SATURATION FOR ACHIEVEMENT OF MAXIMAL OIL RECOVERY BY WATERFLOODING

Investigations of influence of a larger number of favourable and unfavourable factors, shown in the two previous chapters, indicated undisputable usefulness of free and, related to that, trapped gas in the reservoir. Several authors therefore tried to establish the optimal trapped gas saturation which, after waterflooding that follows the primary depletion phase, yields maximal additional oil recovery.

One of the authors, using the program for calculation of regressions with multiple variables, tried to establish a correlation for calculation of optimal gas saturation.[5] He obtained a regression equation with 4 coefficients, which satisfies all sets of data with average absolute variation of 4.6%.

In a more recent paper another author used various models of relative permeability curves.[8] He applied the ones from earlier literature to describe the primary depletion phase with dissolved gas drive and flow in the drainage direction. The others, calculated by him, were used for description of waterflooding and for processes in the imbibition direction. He checked his calculations by applying the Buckley-Leverett frontal advance equation. Based on the calculations, he developed different nomograms to obtain optimal gas saturations depending on differences in oil densities, saturation pressures, pore size distributions and degrees of waterflooding (at water breakthrough, after injection of one or two pore volumes of water). Fig. 7 presents one of the typical results of calculation, which he used, among the others, for development of above described nomograms. The figure shows results of calculation obtained by using oil with density of 876 kg/m³ (30 °API) and average relative permeability curves. It is evident from the figure that for such fluid and pore system, all curves indicate maximal oil recovery at initial gas saturation, or more precisely, at gas saturation present in the moment when water injection started, of about 20%. Use of other combinations of above pa-

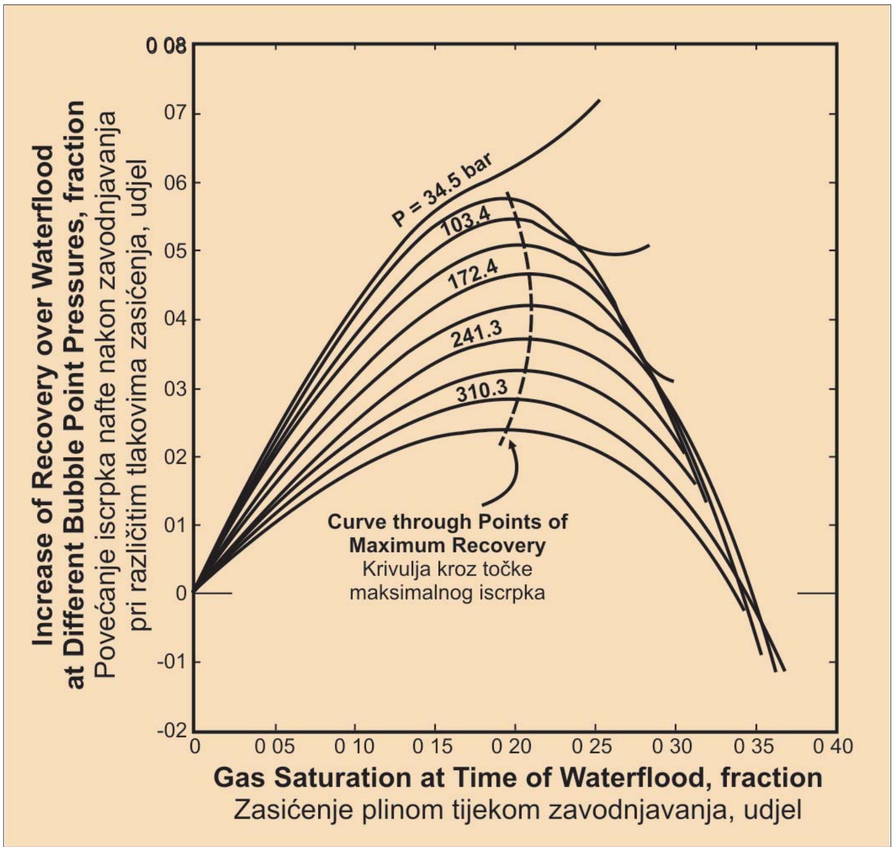

Fig. 7. Increase of total oil recovery depending on initial gas saturation for pore size distribution II, oil density 876 kg/m³ (30 °API), and at different oil saturation pressures[8,11]

Sl. 7. Povećanje ukupnog iscrpka nafte u ovisnosti o početnom zasićenju plinom za raspodjelu veličina pora II, gustoću nafte 876 kg/m³ (30 °API), i pri različitim tlakovima zasićenja nafte [8,11]

rameters gave curves resembling the ones shown in the Fig. 7.[8,11]

5. THE APPLICATION OF THREE-PHASE RELATIVE PERMEABILITIES IN SIMULATION OF WATERFLOODING PROCESSES WITH PRESENT TRAPPED GAS

Several recent papers introduce the results of numerical simulations based on three-phase relative permeabilities.[4,6,9] The first of them describes a simulation of waterflooding process with the presence of gas in a linear system.[9] Reservoir model incorporates the effects of hysteresis in permeability and the entrapment of gas by the oil bank. As an illustration, Fig. 8 shows relative permeability drainage curves for oil (k_{ro}) and gas (k_{rg}), with several relative permeabilities to gas in the imbibition direction.

The curves in the imbibition direction allow simulation of gas trapping after the start of waterflooding. Which krg curve will be activated depends on the degree of reservoir gas saturation achieved in the primary phase of depletion by dissolved gas drive, at which the waterflooding began. The reservoir model incorporates effects of gas compressibility and gas solubility in oil.

Another paper focused even more on the effects of hysteresis, which were applied not only to relative permeability curves, but to capillary curves as well.[6] To some extent, the numerical model is based upon remembering the saturation history of the reservoir, which implies that in continuation of simulation the model takes into consideration the previously achieved final saturation values where the simulated process changes direction. In order to be able to do that, an algorithm that allows calculation of curves of smooth transition (so-called scanning curves) from drainage to imbibition and vice versa, was incorporated into the model. Besides, the model also accounts for the influence of trapped gas or oil saturation on relative permeabilities and capillary pressures. By combining models that include hysteresis effect and applying the equation of three-phase relative permeability to oil, the simulator can more realistically predict residual oil saturations.

The most recent paper describes additional features incorporated into the numerical model.[4] Apart from active hysteresis and three-phase permeability options, effects of composition and interfacial tension (capillarity) on relative permeabilities are also taken into consideration. Correlation for calculation of different relative permeability curves is based on interpretation of the pore-level mechanisms that determine fluid flow. The paper describes a mixed-wet gas reservoir, i.e. a type of reservoir with transient wettability.

6. CONCLUSION

The practical meaning of trapped gas saturation efficiency is that it represents a direct measure of additional recovery in comparison with the recovery that would have been achieved by waterflooding without the gas presence during the entire process, or when gas phase disappears during waterflooding due to compression and dissolution in oil. In line with that, efficiency of trapped gas saturation is expressed in the form of additional oil recovery as a fraction or percentage of the gas quantity that remains in the pore space during the waterflooding process. From the aspect of trapped gas saturation efficiency, review of data confirmed that in most practical cases presence of free gas would certainly have a beneficial impact on oil recovery achieved by waterflooding.

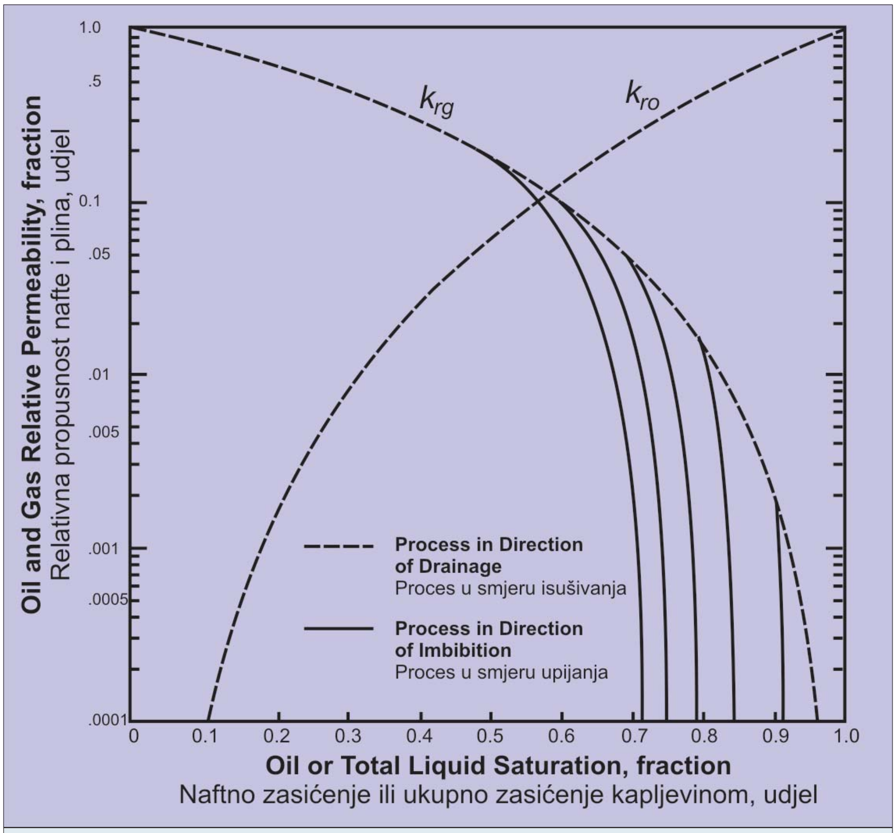

Fig. 8. Drainage relative permeabilities for oil and gas with relative permeabilities to gas during imbibition[9]

Sl. 8. Drenažne relativne propusnosti za naftu i plin s relativnim propusnostima za plin pri upijanju[9]

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