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Some Aspects about Determination of the Saturation State in Oil Reservoirs

Mihai Ciprian Baciu*, Ion Crețu**

* Petrom E&P, Piața Eroilor, 1A, Ploieşti
e-mail: ciprian.baciu@petrom.com
** Universitatea Petrol – Gaze Ploieşti, Bd. Bucureşti 39, Ploieşti

Abstract

The saturation state in oil reservoirs is a very important parameter for reservoir characterization exploited in primary and secondary recovery and also for the application of EOR/IOR methods. Today there are different methods to determine the state of saturation, but these methods can be classified as direct methods (or laboratory methods), e.g. solvent extraction, X-ray tomography, and indirect methods e.g. tracer tests, geophysical methods, 4D seismic, well test, material balance, fractional flow theory. The paper analyses these methods and shows, for each of them, the main characteristics, advantages, disadvantages and the possibilities for applying them in the field.

Key words: *oil saturation, tracer test, geophysical investigation, 4D seismic*

General Aspects

A hydrocarbon reservoir is defined as a complex system made up of a solid part (reservoir rock) and the fluids that fill the pores of the rock. Between rocks and fluids occur complex interactions.

Fluids (water, oil, gas) are always present in the pores of the rocks and the saturation concept reflects the degree and the way in which the pores are filled. Because there is not just a single fluid present in the reservoir, each of the fluids present in this space will participate in different quantities in the saturation coefficient. In this case it is possible to define a saturation parameter for each fluid phase present in the reservoir, S_i, as the ratio between the volume of each fluid phase, V_i, and the total pore volume V_p:

$$S_i = \frac{V_i}{V_p} \tag{1}$$

It is easy to notice that each saturation coefficient is a positive number lower than 1 and the volume balance law is:

$$\sum S_i = 1 \tag{2}$$

The saturation state of a hydrocarbon reservoir is a key parameter in the evaluation of hydrocarbon resources, in the evaluation of EOR and IOR processes applied before, or as a possibility to apply it in the future.

It is very important to know that saturation state is not a static parameter during the whole reservoir's "life"; during reservoir exploitation the saturation state is changing. Thus, in an oil reservoir with greater pressure than the initial saturation pressure in the reservoir, we will find only oil and connate water. If the pressure decreases lower than the saturation pressure, the gas will go out of the solution and the saturation state will change in the reservoir. The implications of this change are major for reservoir exploitation.

Methods to Determine the Saturation State

The methods to determine the saturation state can be classified in two main groups:

- direct methods, (or laboratory methods) which use cores to determine the saturation state. The most common methods are: solvent extraction, fluid balance, X-ray tomography;
- indirect methods. These methods are used to measure another reservoir parameter (resistivity, pressure, concentration in different chemicals) and the saturation state is calculated afterwards. These methods are: tracer tests, geophysical methods, hydrodynamic investigations, material balance, relative permeability – saturation relationships involved in the fractional flow theory particularized for water flooding, solvent flooding, micelare – polymer flooding, alkaline flooding and foam flooding [1, 9, 10, 11].

Direct methods

Solvent extraction method

The core sample is continuously washed with hot solvent. For determination of saturation state it is necessary to know the pore volume of the sample and the fluid volume. The pore volume can be determined using different kinds of methods [2] and it is supposed to be known when the saturation is determined.

The apparatus used in the lab allows boiling off the water from the rock sample and also its measurement. The oil is removed from the rock sample by the distillation of the volatile fraction and the dissolution of heavy components. In this case, the oil volume is not measured, but it is calculated in an indirect way.

Fluid balance method

This method is the most simple among the non-destructive methods. In order to determine the saturation, the injected and extracted fluids volumes are precisely recorded at specific time intervals. If the initial fluids volumes are known, it is very easy to calculate the saturation at every time step. This method requires very precise laboratory apparatuses.

X-ray tomography

This method has the best results among all non-destructive methods. X-ray tomography is a possibility to radiography the opaque objects and to determine density and atomic composition. The result of tomography is an image or a succession of color images of transversal sections through the object.

In this type of investigation the rock sample is irradiated with an X-ray bundle. The intensity of X-ray at the admission of rock sample is different from the intensity out of issue. The X-ray intensity will be attenuated according to the rock thickness and properties.

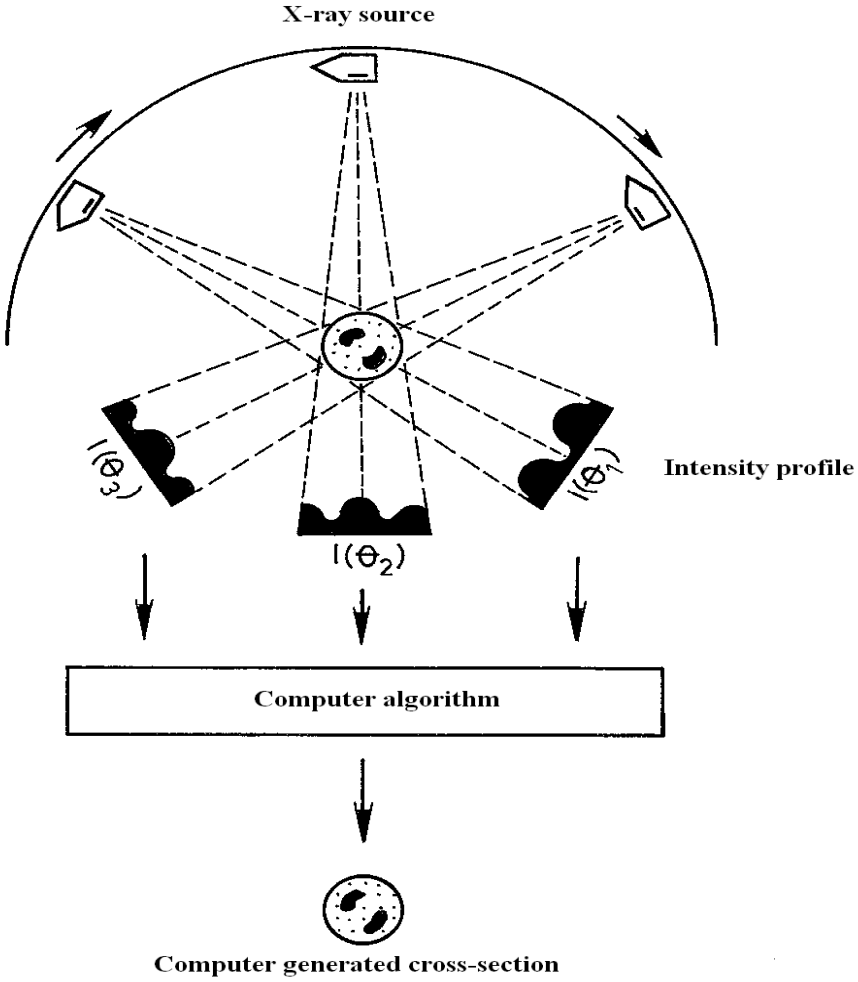

Fig. 1. X-ray tomography principle [2].

Indirect methods to determine saturation

Material balance

Material balance is usually used to calculate hydrocarbon resources, but if the values for hydrocarbon resources and reservoir parameters are already known, material balance can be used to calculate the saturation.

The most generally form of the material balance equation the one referring to an oil reservoir with water drive, water and gas injection, is [3]:

$$\Delta N = \frac{N(u-u_i)+(W_i-W_pB_w)+G_iB_g}{(R_p-r_s)B_g+u} + \frac{\frac{u_i}{1-S_{ai}}\left[\left(c_f+S_{ai}c_w\right)\Delta p\right]+\frac{mu_i}{B_{gi}(B_g-B_{gi})}+W_e}{(R_p-r_s)B_g+u}, \quad (3)$$

where: N, ΔN – oil in place, cumulative oil; m – the ratio between gas cap volume and oil saturated zone; W_i, W_p, W_e – injected, produced and in flowed cumulative water in the productive area; Δp – the subtraction between initial and actual pressure; R_p – cumulative gas/oil ratio; S_{ai} – initial water saturation; u, B_t, B_g – oil and gas volume factors; r_s – solution gas ratio; c_f, c_w – formation and water compressibility.

If the pore volume is known, it is possible to determine oil saturation at different time periods (in the past or as forecast) using the following equation:

$$S_t = \frac{(N - \Delta N) B_t}{V_p} \tag{4}$$

Fractional flow theory

The definitions for recovery, displacement and sweep efficiency apply to an arbitrary chemical component are almost exclusively applied to oil and gas displacement in porous media. Since displacement efficiency and sweep efficiency are multiplied by each other, theory are equally important to the magnitude of the recovery, efficiency and, hence the oil recovery.

Using Buckley-Leverett solution we can determine the average injected fluid saturation before and after breakthrough [1, 9, 10, 11].

Tracer tests

The tracer is a chemical substance which is not naturally present in the reservoir fluids, but can be carried by them along with their flow through the reservoirs and it is easily detected in very low concentrations.

The tracer tests are generally used in oil industry since 1968 when the first test was conducted. There are different kinds of tracer tests:

- tracer tests conducted to identify the flowing pathways, water fingering, geological fingering, fracture sealing, without application in saturation determination;
- tracer tests conducted to determine oil saturation in one well or between two wells; the latter offers the advantage of a broader investigation.

Tracer tests can be conducted in single-well when this is used for tracer injection and also for producing the fluids, or can be conducted in dual-wells, one used for injection and the other for producing the fluids.

In tracer tests the oil saturation can be calculated using the relative velocity of the two tracers scattered in the porous area. Because the fraction between the relative velocities of the two tracers depends on one hand on the oil saturation and, on the other hand on the relative solubility of the two tracers in water and in oil, it is possible to determine the saturation in oil if the relative solubility is measured in the laboratory.

Single-well tracer tests

The field procedure includes 3 phases:

a. Injection phase

During this phase, the primary tracer A is injected into the reservoir, using brine (usually water from the same well or reservoir). This tracer is soluble both in water and oil. The tracer will hydrolyze in the reservoir with a known reaction rate, resulting another tracer, the secondary one B, soluble only in oil. Using a slug of brine without tracer, the brine containing the primary tracer is injected into the reservoir up to a finite distance from the injection well. The volume of the second slug determines the radius of investigation of the tracer test.

b. Reaction phase

In this period the well is shut down for hydrolyze reaction mentioned above. After the primary tracer A has arrived in the reservoir, which is saturated for example in water and oil at residual saturation, the tracer will divide into oil and water at balanced concentration in each of them.

Because the water is the only mobile phase, the velocity of tracer in porous area is lower than the velocity of the injected water, and it depends on the velocity of water, partition coefficient and the residual oil saturation.

The oil saturation can only be measured using the secondary tracer, B, because this tracer is not naturally present in the native brine of the reservoir and can be detected in very low concentrations.

At the end of the shut down period the two tracers, the primary one non-hydrolyzed and the secondary one produced in the reservoir, are present together into the reservoir up to 6 – 8 m from the well.

c. Production phase

After the hydrolyze reaction takes place, the well is re-opened and the concentration of the primary and secondary tracer, as well as the volume of produced fluids are measured at precise time periods.

Because the partition coefficient of the primary tracer is not the same for water and for oil, the two tracers will have different velocities in the reservoir and will be detected at different time intervals. Using this time difference it is possible to calculate the oil saturation, S_{pr}, with the equation:

$$S_{pr} = \frac{\beta_i}{\beta_i + k_i} \tag{5}$$

where β_i is the delay coefficient and k_i is the partition factor.

The partition factor, k_i, is defined as the fraction between the concentrations of tracer in oil land in water:

$$k_i = \frac{(c_i)_p}{(c_i)_a} \tag{6}$$

To determine the delay coefficient (β) it is possible to use the fraction of travel time (t) of the two tracers:

$$\beta = \frac{v_A}{v_B} = \frac{V_B}{V_A} = \frac{t_A}{t_B} \tag{7}$$

Where V_A and V_B are the volumes of the two tracers (A, respectively B), v_A, v_B, are the velocities of tracers.

Dual-well tracer tests

For tracer tests conducted in two wells it is used the landmark method for test design and saturation determination. This method was proposed by Tang in 1991. Because the tracers injected into the reservoir have the same direction of flow, but different travel times, the response curves of the two tracers should be similar. The saturation can be determined using the response curves (the variation of concentration in the tracer and the time in the reaction well), if an initial time is considered on each curve.

If we consider $c_p(\tau)$ the concentration of the tracer soluble only in water, and $c_n(t)$ the concentration soluble both in water and oil, τ and t are the time references (the time when they appear in the well) of the two tracers, and the values of the concentrations are normalized by dividing them by the maximum concentrations from the response curves, the two values become equal:

$$\frac{c_p(\tau)}{c_p(\max)} = \frac{c_n(t)}{c_n(\max)} \tag{8}$$

Marking τ/t the fraction between the arrival times in the well for the two tracers, we can write:

$$\frac{\tau}{t} = (1+\beta) = \left[1 + k_i \frac{S_{pr}}{1 - S_{pr}}\right] \tag{9}$$

This relation allows determining the oil saturation, S_{pr}, if we know the partition coefficient β.

For tracer tests achieved in two wells is very useful presence of observation wells. These wells are located between injection well and reaction well and tracing the tracer in reservoir. In these wells can be performed geophysical investigation (gamma ray) and fluid analysis. It is very important that fluid analysis (their volume and frequency) not affect the pathways in the reservoir.

The main disadvantage for observation wells is the cost, but it is possible to decrease the costs by using old production wells.

Determining saturation by geophysical methods

Neutron logging

The Pulse Neutron Logging, PNL is a method to identify the by-passed area in hydrocarbon reservoirs. There are two kinds of PNL: Pulse Neutron Capture (PNC) and Pulse Neutron Spectroscopy (PNS). The PNC logging is affected by diminution of sensibility in low or variable salinity media. Instead PNS is not influenced by salinity. PNC is relatively independent of the steel content of the tubing and casing, but PNS records information from a large area.

Magnetic nuclear resonance

In this kind of investigation a permanent magnet generates a magnetic field in the area around the reservoir. The antenna sends trains of radio waves into formation which create an oscillating magnetic field. Between these wave trains the antenna listens the echo of signals from the hydrogen protons that go in resonance with the permanent magnetic field.

The main components of a Nuclear Magnetic Resonance apparatus are:

- a permanent magnet;
- an antenna that surrounds the permanent magnet.

A Nuclear Magnetic Resonance can directly measure the density of the hydrogen nuclei based on linear dependence relation between the protons resonance frequency and the intensity of the magnetic field. Because the density of hydrogen nuclei in water is known the information obtained from a NMR investigation can be directly converted into porosity data, without the need of any other information like the minerals present in the rock or the chemical elements that could disturb the investigation.

The electromagnetic investigation between wells

Schlumberger has developed a new type of hydrocarbon investigation at large scale: electromagnetic investigation that operates at frequencies from 1 to 1000 Hz and the distance between wells could reach 300 – 500 m for cased wells or even 1000 m for open holes.

The contrast between resistive hydrocarbons and conductive formation water is the basis for hydrocarbon detection. The underlying physics principle of cross-well EM survey is the same as

that of the borehole induction logging tool: magnetic dipole transmitter T (loop) induces currents in the formation surrounding the borehole (10^5 times stronger than borehole induction tools. Induced current depends on the transmitter (moment) strength, operating frequency and the formation conductivity and it is inversely proportional to square of distance). Receiver R detects direct field (primary) and induced field (secondary); secondary field (formation) is typically 10 % ~ 50 % of the total (fig. 2, 3). Formation resistivity is derived from secondary field measurement by the inversion process. The receiver is made of sensitive elements which are, in fact, thousands of magnetic cores with high magnetic permeability. This fact allows measurements with high accuracy for a maximum distance of 1000 m distance between wells.

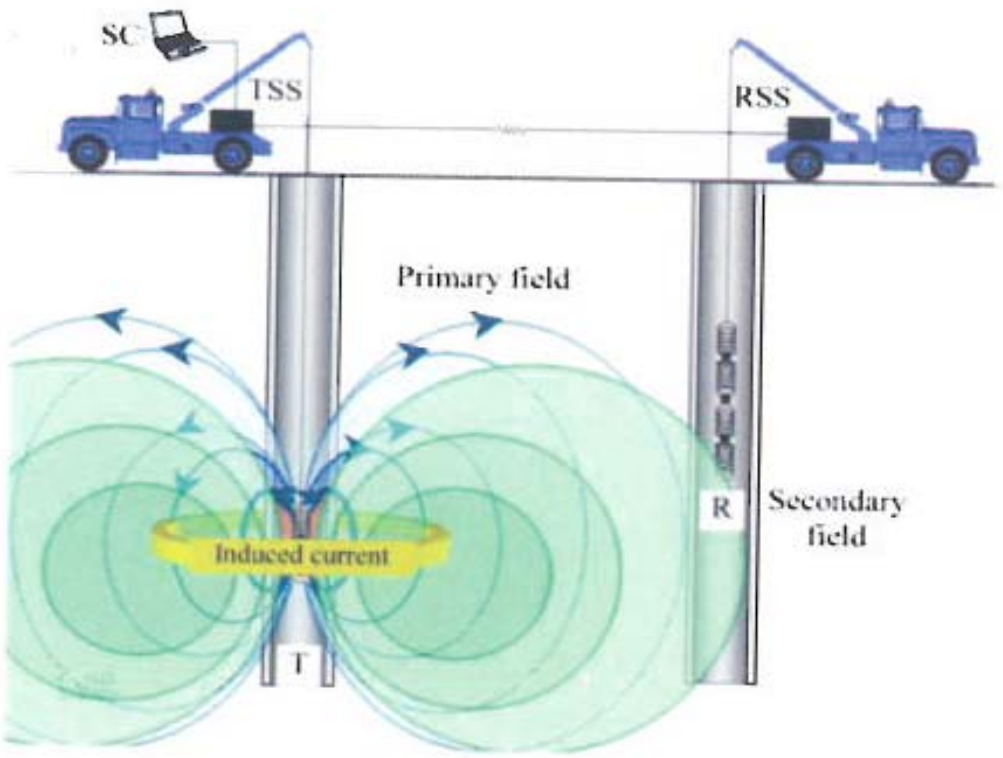

Fig. 2. The principle of electromagnetic investigation [6]

During the investigation the receiver is stationary at one definite depth in the well and the receiver is moving between the two depths in the reaction well. After that, the receiver is located at another depth and the operation is rerun. By positioning the instruments at different depth values it is possible to achieve data in order to proceed a spatial interpretation of distribution saturation between the two wells.

A typical investigation is taking approximately 8 - 24 hours for 1000 ft vertical section. The error of collected data is less than 1 %. The electromagnetic investigation can be performed in cased wells or in non-cased wells (open hole). For the last ones, the intensity of signal is lower and this leads to narrowing the radius of investigation. The values for the radius of investigation are presented in table 1, for different types of wells [5].

Table 1. Radius of investigation for electromagnetic method

Type of well	Distance, m
Open hole/open hole	1000
Open hole/cased well	500
Cased well/cased well	300

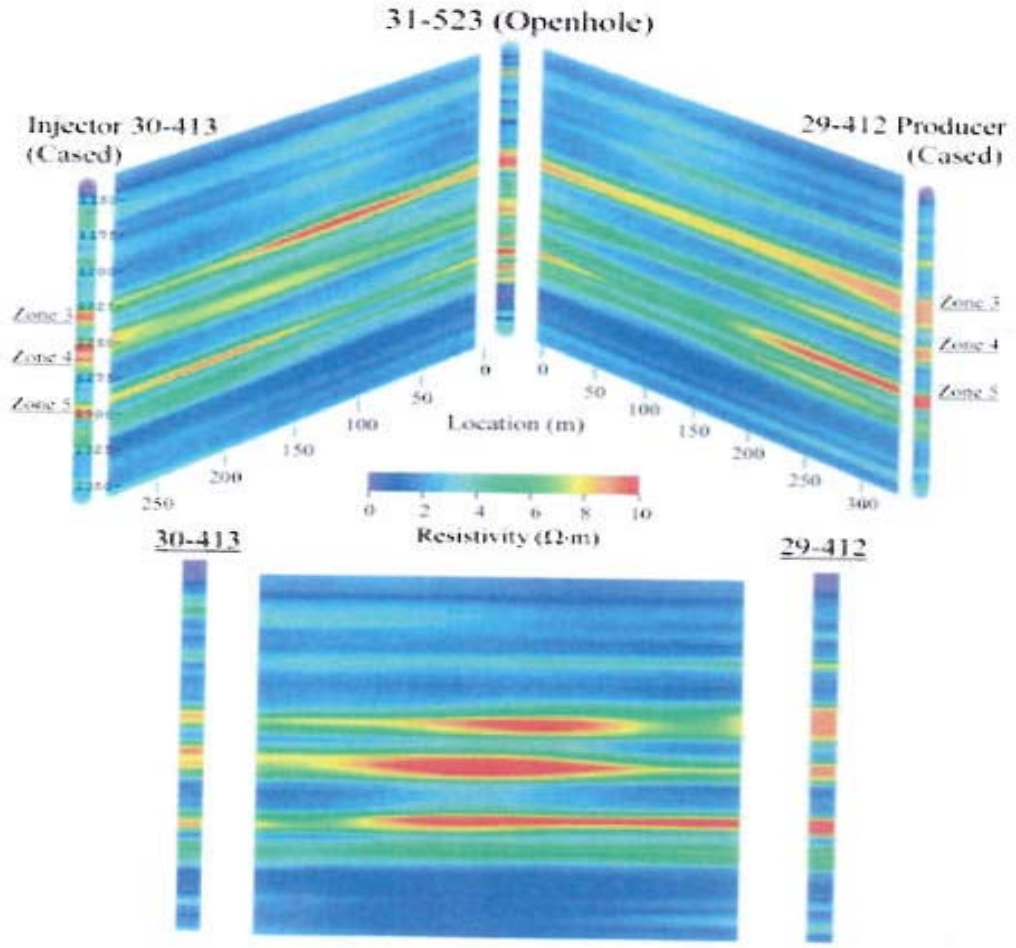

Fig. 3. Electromagnetic investigation case study
The distance between the wells 412 and 413 is 265 m.

4D seismic

In a 3D seismic investigation a seismic source (dynamite, air gun) generates seismic waves near the surface of the earth. These waves are reflected by the surfaces that present an impedance contrast and they depend on fluids and rock compressibility, density, shearing mode. At the surface, these reflected waves are recorded by receivers (geophones for on-shore area and hydrophones for off-shore area). Using a computer algorithm, it is possible to create a 3D image of the reservoir based on the recorded train waves.

To obtain 4D seismic, it is necessary to repeat 3D seismic at another time moment; the time represents the fourth dimension. Using 4D seismic it is possible to monitor the processes in the reservoir and the changes that appear. The 4D seismic offers all the benefits of 3D seismic and the major advantage of visualizing the fluid flow in the reservoir. The seismic images are sensitive to reservoir invariable properties (lithology, porosity, clay content) and depend on time variable properties (fluid saturation, temperature).

Actually, the 4D seismic conducted off-shore is the most used method worldwide, due to some factors that ease the application of this method in the area, but it can also be performed in on-shore reservoirs, for gas reservoirs, for heavy oil reservoirs exploited using SAGD.

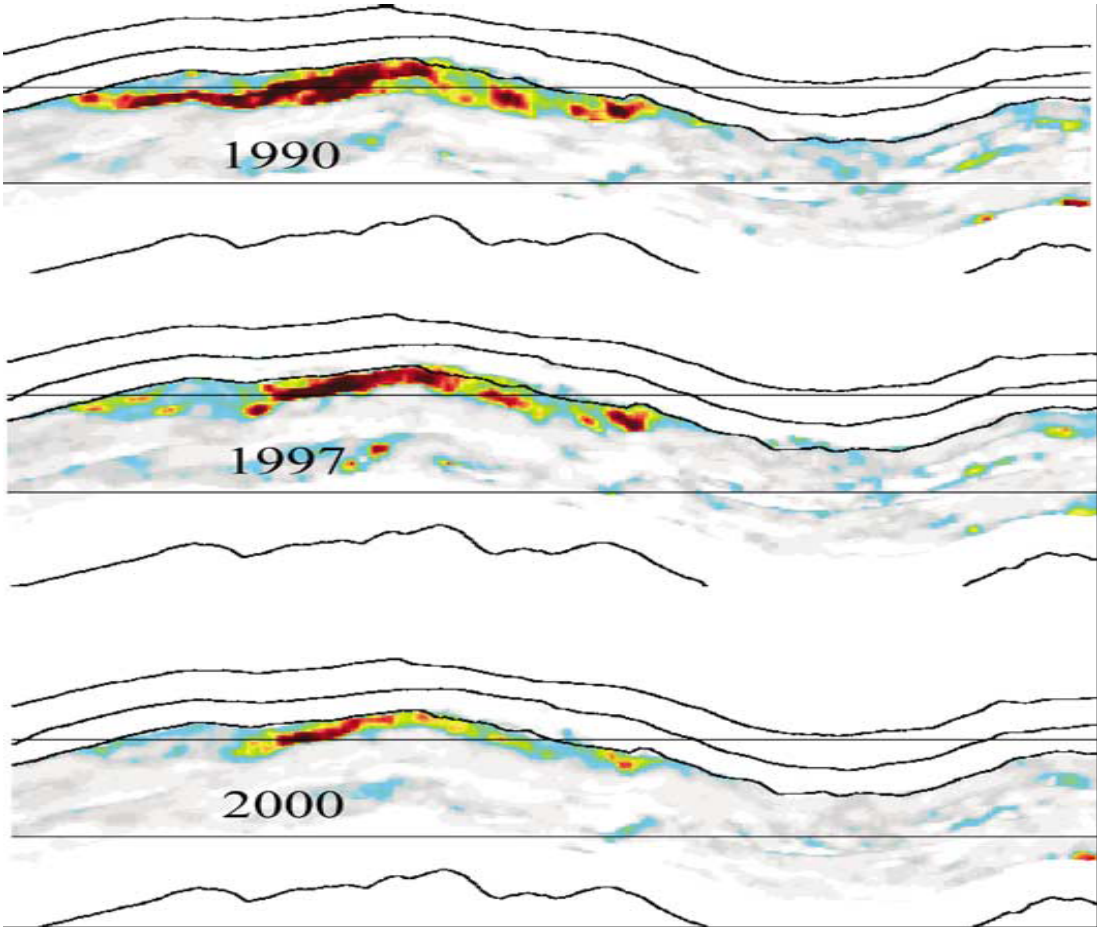

Fig. 4. The probabilistic representation of oil saturation in a reservoir at different time periods obtained from 4D seismic. The red zones have high oil saturation and the blue ones have low oil saturation [7].

Conclusions

1. The saturation state in hydrocarbon reservoirs is very important for reservoir characterization, for resource calculation and for analysis of EOR/IOR methods applied in the past or proposed to be applied in the future.
2. In order to determine the saturation state two kind of methods could be used: direct or laboratory methods, like solvent extraction, fluid balance, X-ray tomography, and indirect methods applied at a large scale directly into the reservoir like: tracer tests, hydrodynamic investigation, geophysical methods: neutron logging, nuclear magnetic resonance, electromagnetic investigation, 4D seismic.
3. In this paper, these methods are presented in short, among direct methods X-ray tomography is a modern and non-destructive method.
4. Tracer tests have many advantages and for oil reservoirs in Romania can be a very useful method to determine the actual saturation state.
5. The paper also presents the geophysical methods, showing the advantages and disadvantages for each of them.
6. Electromagnetic investigation between wells has a very good radius of investigation and offers a good image of the reservoir.

7. The 4D seismic is a little bit difficult to use for direct determination of saturation state, but it is very attractive for visualizing the changes in fluid contacts in time.
8. When possible, it is recommended to use at least two different methods to determine the saturation state.
9. Even though the methods presented in this paper seem very attractive, still determination using cores must be done, while many geophysical methods need these kind of data for calibration.

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Metode pentru determinarea stării de saturaţie din zăcămintele de petrol

Rezumat

Starea de saturaţie din zăcămintele de hidrocarburi reprezintă un parametru foarte important în caracterizarea acestora, atât în faza primară a exploatării, pentru calculul resurselor de hidrocarburi, cât şi în fazele secundară sau terţiară a exploatării, respectiv în decizia de a aplica metode de recuperare îmbunătăţită a petrolului. Metodele pentru determinarea stării de saturaţie pot fi clasificate ca metode directe (de laborator) ce includ extracţia cu solvenţi, tomografia cu raze X, bilanţul de fluide şi metode indirecte: teste cu trasori, metode geofizice, investigaţii seismice 4D, investigaţii hidrodinamice, metoda bilanţului material. În lucrarea de faţă sunt prezentate pe scurt aceste metode cu avantajele, dezavantajele şi caracteristicile fiecăreia, precum şi posibilităţile de aplicare.