

LABORATORY MEASUREMENT OF THE RESIDUAL GAS SATURATION

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Abstract : The determination of residual gas saturation by water drive is based on various types of laboratory coreflood experiments. Using systematic cross checks, we have compared the results obtained by the various techniques, and penalizing effects observed in each experiment (effect of trapped gas compression for flooding experiments, effect of trapped gas diffusion for spontaneous imbibition experiments) have been investigated. Some emphasis has been given to the study of this diffusion process, which has been found to be very important at ambient conditions but negligible at reservoir conditions. Finally, we propose simplified but reliable procedures for the determination of the residual gas saturation.

INTRODUCTION

To evaluate the quantity of gas which can be produced from a gas field with natural water drive, it is critical to know the residual gas saturation behind the water front.

In this paper, we will discuss only the trapping of gas at constant pressure, keeping in mind that the effect of pressure decline on trapped gas decompression should be also considered.

However, the measurement of the residual gas saturation (S_{gr}) is quite critical, as this value may range over a wide interval, which is a function of :

the texture of the porous network : aspect ratio (pore diameter/throat diameter) ;

- the total clay content, and location of clays minerals in the pores.

We have found values of Sgr ranging between :

- 60 to 70 % for vuggy dolomites, poorly connected vugs ;
- 10 to 15 % for chalk with low aspect ratio ;
- 15 to 40 % for various sandstones (various degrees of cementation and clay content).

Several authors (4, 5, 6, 7, 8) have already studied this problem of Sgr measurement, with various procedures (water injection or water imbibition through a porous plate) under various experimental conditions (laboratory or reservoir conditions).

We have extensively investigated this problem for one of our North Sea Gas fields, with unconsolidated to poorly consolidated sandstone reservoir samples. We have performed the same type of experiments as already reported, but we also included experiments of gas trapping by spontaneous imbibition. A phenomenon of trapped gas diffusion was observed and investigated in detail.

Finally, we have compared our laboratory results with field data (from openhole resistivity logs) and validated simplified laboratory procedures.

LABORATORY PROCEDURE AND APPARATUS

Core sample characteristics

They are mainly :

- clean sand samples, cored with rubber sleeve,
- more or less shaly sandstone samples, poorly or non consolidated,
- Berea sandstone samples.

Fluids

For the various experiments, we have been using :

- brine with 55 g/l NaCl, without dissolved gas,
- brine with 55 g/l NaCl, saturated with gas at the experimental conditions,
- soltrol paraffinic mineral oil,
- nitrogen or methane.

The surface tension of water varies between 72 dynes/cm (ambient conditions) and 40 dynes/cm (165 bars, 60°C). The surface tension of the Soltrol oil is 23 dynes/cm.

Preparation of the samples

- For the poorly consolidated sandstone, we first coat the sample with a twin polyester polyolefine film, to avoid any further gas diffusion. Then the sample is installed in a viton sleeve, and isotropic overburden pressure is applied (figure 1).
- For the sand facies, the samples (length shorter than 56 cm) are taken with a specially designed puncher, then transferred in a twin butyl/viton sleeve, in order to avoid gas diffusion and to allow cleaning by solvent injection. A triaxial overburden pressure is applied to avoid from lateral deformation of the porous medium (figure 1).

By doing that, we prevent any radial (permeability) heterogeneity, which can be penalizing for the representativity of two phase flow experiments. It is a risk that heterogeneity along the axis of the core is existing, but this is less critical.

The overburden pressure applied in the triaxial coreholder is satisfying the condition :

$$dV_P = dV_T = AdL + LdA$$

(nomenclature at end of paper).

To satisfy this relation, we generally apply an effective horizontal stress equal to 0.4 times the effective vertical stress. This procedure also prevents the core sample from buckling, when too long.

Trapping of gas by waterflooding, ambient conditions

The connate water saturation is obtained by draining a water saturated sample with dry nitrogen, then evaporating by flooding with the mentioned gas (the flow direction being periodically changed).

The evaporation process is controlled with two columns with water absorbing chemicals, and the final connate water saturation is computed by material balance. It is controlled either by weight measurement or by a quick gas decompression, following a $\frac{P}{Z}$ relationship.

The displacement of gas by water is achieved at constant flow rate Q or at constant differential pressure ΔP , with an outlet pressure P_S ; the procedure is adapted to the characteristics of the sample.

We must keep in mind that the gas is trapped at the water front, under capillary equilibrium, at a pressure equal to $P_S + P_C$ (pressure drop in the gas zone neglected).

Then the gas is compressed when the water front advances through the core, up to a pressure equal to $P_S + P_C + \frac{\Delta P}{2}$ at water breakthrough.

Because the pressure drop is small compared to the initial pressure in the reservoir, we will have to determine S_{gr} at the water front, i.e. at a pressure equal to $P_S + P_C$. As a consequence, it will be necessary after the water breakthrough to decompress the system down to P_S to measure S_{gr} ; this decompression effect may be small if P_S is well chosen and if ΔP is small compared to P_S .

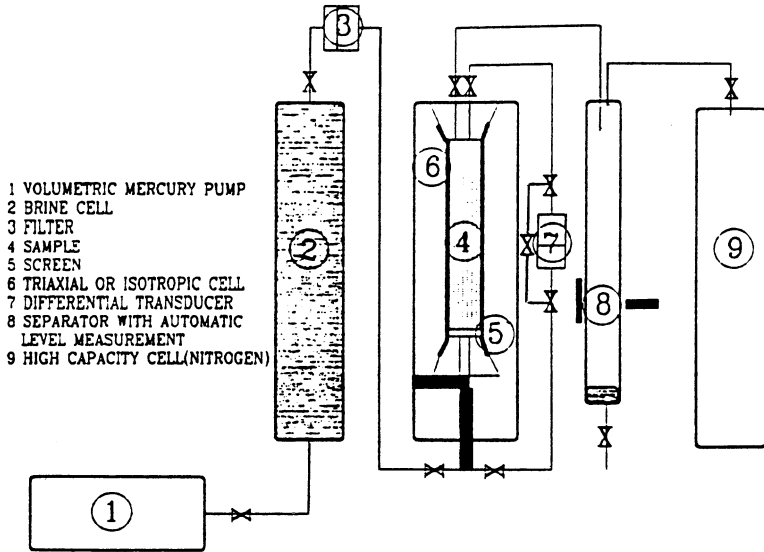


Fig 1 Apparatus for water flooding
Ambient conditions

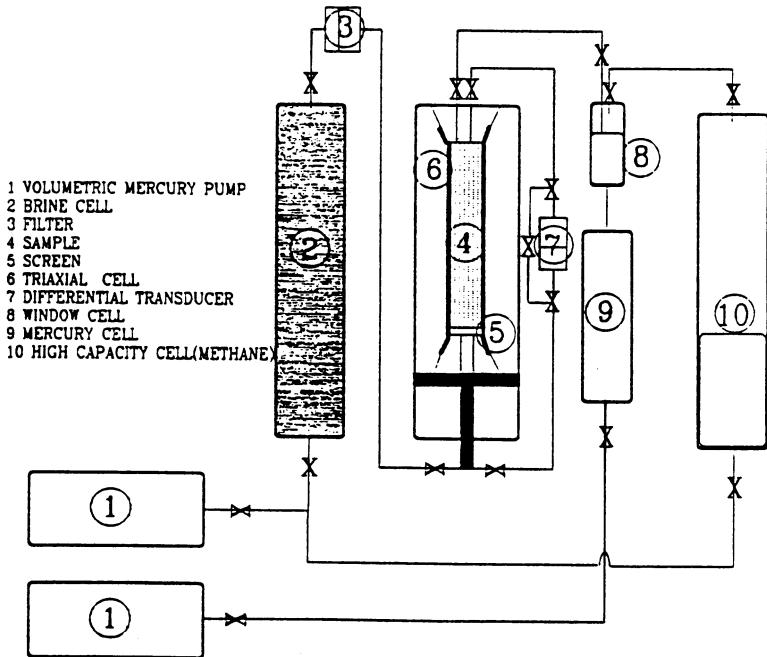


Fig 2 Apparatus for water flooding
Reservoir conditions

* Experimental device :

It is described in fig. 1, and includes :

- a volumetric injection pump,
- a fluid cell with brine saturated with gas at the average flowing pressure,
- an isotropic or triaxial coreholder,
- pressure gauges,
- an optic separator, with automatic level measurement,
- a large capacity cell to maintain the outlet pressure.

Trapping of gas by waterflooding, reservoir conditions
fig. 2

The brine is first saturated with methane at experiment temperature and pressure.

The core samples which are studied here have a rather high permeability, which means that the pressure drop while flooding is negligible as compared with pore pressure, which is kept constant. The injection is achieved with a constant injection and withdrawal rate. During and after water breakthrough (detected by an increase of ΔP), the cumulative gas production is measured by monitoring a gas/liquid level in an optical cell (the flow is temporarily and shortly stopped for these measurements).

Trapping of gas by capillary rise

The basis of this experiment is quite simple, see fig. 3. We periodically measure the weight increase of a sample with the lower end slightly immersed in liquid (water or oil), all the system being kept in air saturated with liquid vapor (no evaporation).

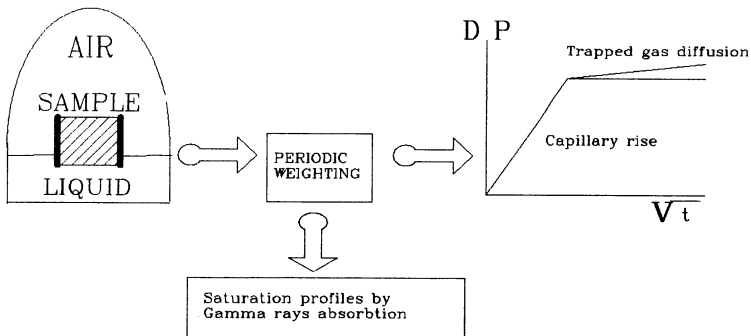


Fig 3 Apparatus for gas trapping by capillary rise.

We generally observe two trends in the relationship between weight and square root of time :

- the first step, with a steep slope, corresponds to the advance of the liquid front through the sample by capillary rise. The relationship is linear if capillary forces are large compared with gravity forces ;
- the second step, with a **smaller** slope, occurs after the liquid front has reached the upper face ; it denotes a trapped gas diffusion process, which will be studied in depth.

The intersection point of the two lines allows to determine the maximum residual gas saturation S_{grM} .

RESULTS

Waterflooding

A series of experiments have been performed on three clean sand samples and one sandstone sample with low clay content. The main flow direction has been kept vertical, flowing upwards, and various parameters have been changed :

- sample length,
- injection rate : velocity ranging from a value close to the reservoir one (6 cm/day) to a value computed according to Rapoport criterion ($LV\mu = 1$) (10),
- ambient conditions or reservoir conditions (PFluid = 156 bars, T = 60°C), with fluids in thermodynamical equilibrium. The surface tension of water has changed from 72 mN/m to 40 mN/m,
- connate water saturation : from zero to 20 % PV.

The results obtained after a cumulative injection of 1 to 2 pore volumes of brine (table 1) show that, after correction for the small variations of petrophysical characteristics (porosity), the residual gas saturation Sgr is not affected by :

- the length of the core sample (27 to 56 cm),
- the injection rate ; this point will be discussed later, in the paragraph about gas diffusion,
- operating conditions : ambient vs reservoir ; this means negligible effect of the surface tension.

However, a strong sensitivity to the value of connate water saturation is found, which is in agreement with Land theory (11) :

$$\frac{1}{Sgr} - \frac{1}{Sgi} = \frac{1}{SgrM} - 1$$

The results of this phenomenological investigation have allowed to validate several series of earlier measurements, and to get a relationship Sgr VS ϕ with Swi = 10 %.

We have then observed a good agreement between laboratory measurements and field measurements from openhole resistivity logs. These last values correspond to average values over reservoir thickness of 15 to 20 m.

Capillary rise method

This series of experiments has been performed at ambient conditions, with two sandstone samples from the actual reservoir, and with a set of Berea sandstone samples which behave the same way as reservoir samples :

origin	avg. porosity	avg. gas perm
reservoir	30 %	860 mD
Berea	24.1 %	1 000 mD

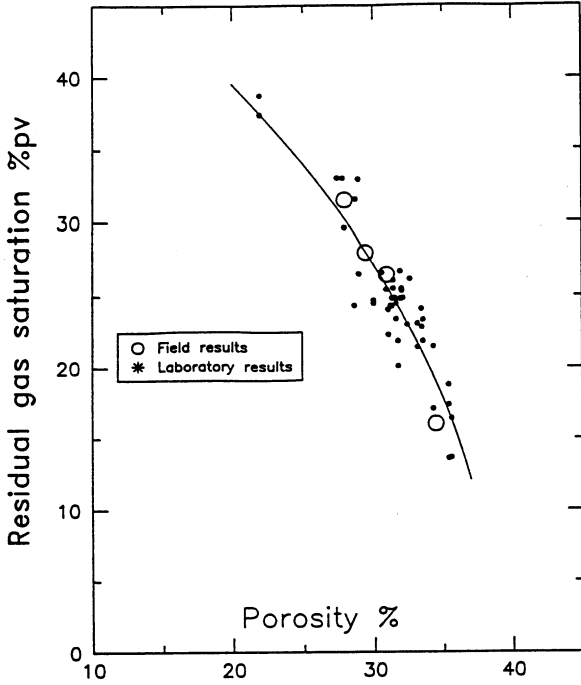


Fig 4 Residual gas saturation ' versus porosity

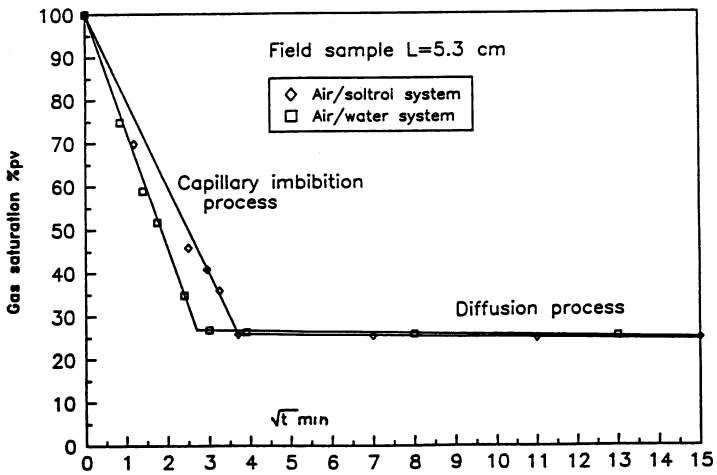


Fig 5 Gas saturation versus time

Nineteen experiments have been performed with various boundary conditions, various fluid systems, over periods of time ranging from 20 to 110 days.

We used mainly Soltrol paraffinic oil ($\mu_o = 1.5$ cP) because it does not react with the matrix (as opposed to water), and allows numerous tests on the same sample.

In some cases, we also used a 55 g/l NaCl brine, in order to investigate the effect of the liquid on the Sgr determination and the diffusion process ; some barium chloride was also dissolved, to allow measurement of saturation profiles by gamma ray absorption.

On the shaly sandstone reservoir sample, we checked that Sgr obtained by water flooding was quite identical to Sgr obtained by spontaneous water imbibition, with the procedure shown in fig. 5 :

Sgr waterflooding = 27.0 % VP, with $\phi = 29$ %,
Sgr imbibition = 26.8 % VP, with $\phi = 30$ %.

These results were obtained with a gas/water fluid system, but we have also performed comparison tests with the gas/soltrol system and observed a Sgr value of 25.7 %, very close to the Sgr mentioned above (the slight difference may be due to the change in surface tension).

Diffusion of gas measured in connection with capillary rise tests

At the end of the gas trapping period, we kept the samples at rest, just monitoring the weight increase versus time ; In some cases, we have observe a decrease of the gas saturation from 33 % to 2.6 %, in a 90 days period of time.

This drastic decrease of gas saturation cannot be explained by a dynamic effect (sweeping) or thermodynamic effect (equilibrium between the gas concentration in the oil phase at the upper and lower face of the sample), as the oil is not flowing during this period.

Such saturation changes could rather be attributed to diffusion phenomena, as already reported by some authors (1, 2, 3, 9).

The drive of this diffusion is linked to the extra gas concentration of the liquid surrounding the gas bubbles. We know from Henry's law that the equilibrium concentration of solution gas in a liquid is proportional to the partial pressure of the gas in contact. We also know that the trapping mechanism of the gas by a liquid occurs with a gas overpressure equal to the capillary pressure, which itself is proportional to the partial pressure : The capillary pressure increases when the bubble radius becomes small.

Hence, the gas will migrate by diffusion from a small bubble to a larger bubble and to the sample face :

- in contact with gas, where the gas/liquid interfaces have a larger curvature radius ;
- in contact with liquid, where the gas concentration is constant and smaller than in the sample if the volume of liquid is large enough, which is the case in our experiments.

Quantification of the diffusion

The capillary rise and diffusion experiments have been performed with samples of various length, and with various boundary conditions : samples laterally sealed with resin, or not.

We established two kinds of relationship between S_{gr} and time (during the diffusion period) :

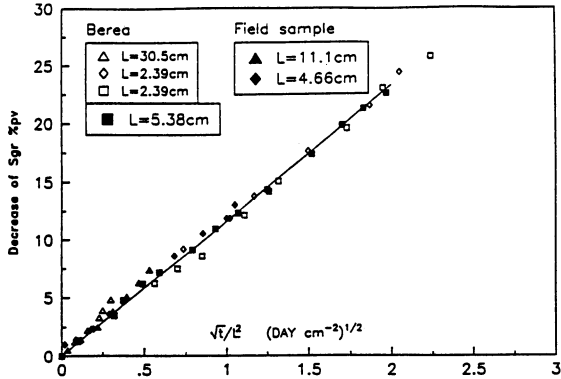


Fig 6 Diffusion of trapped gas air/soltrol system
Samples laterally sealed

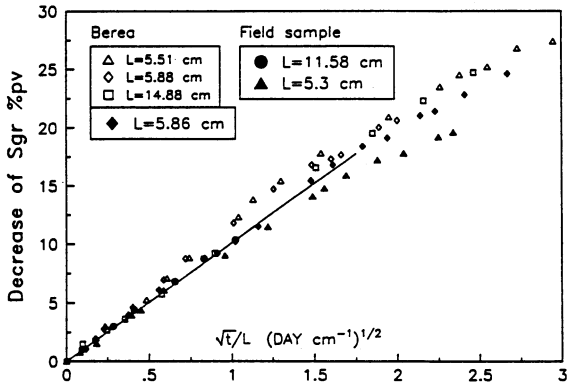


Fig 7 Diffusion of trapped gas air/soltrol system
Unsealed samples

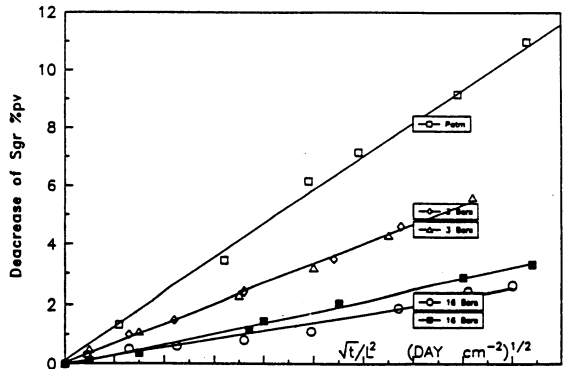


Fig 8 Diffusion of trapped gas : effect of pressure

$$\Delta S_{gr} = 11.5 \sqrt{\frac{t}{L^2}} \quad \text{for the samples laterally sealed (fig. 6)}$$

$$\Delta S_{gr} = 10.15 \sqrt{\frac{t}{L}} \quad \text{for unsealed samples (fig. 7)}$$

with :

$$\begin{array}{ll} \Delta S_{gr} & \% V, \\ t & \text{days}^2, \\ L & \text{cm.} \end{array}$$

The diffusion speed is increased when the surface is in contact with liquid instead of gas ; when operating with the gas/water system, exchanges are slowed down (by a 0.53 factor), as compared with gas/solntrol.

On Berea samples 5.3 cm and 15.5 cm long, with the gas/water system, we have recorded gas saturation profiles : they are always uniform (no saturation gradient along the core), the decrease of Sgr versus time is constant along the core, without formation of any front from the exchange face (outlet face).

Experiments at moderate pressure (capillary rise test)

With an adapted experimental device, which prevents gas diffusion towards the bottom of the sample in contact with oil, and at moderate pressure (3 and 16 bars), we have observed that the exchange is inversely proportional to \sqrt{P} abs (fig. 8). Therefore, we can anticipate that the diffusion phenomena will be of small importance at reservoir conditions.

Modelling

We noted a rather good agreement between our average saturation values and the ones computed using the Mc Worther, Corey and Adams Model, although this model is based on the translation of a zero gas saturation slice from the exchange face (outlet face) which was not observed in our experiment.

Scaling up of waterflooding and diffusion process

Several floods of gas by water have been achieved on two Berea samples, changing :

- the injection rate : water front advance from 1.7 cm/d to 78 cm/d - larger diffusion exchanges are anticipated at low rate ;
- operating conditions : ambient conditions with air/brine system, reservoir conditions (165 bars, 60°C) with methane/brine system.

For some experiments, the outlet end piece of the coreholder includes a large volume of liquid, to improve diffusion exchanges ; this volume is filled after the water breakthrough.

..... Ambient conditions experiments results

- The saturation profiles are different depending on the injection rate :
 - piston-like profile at high injection rate (78 cm/d) with small transition zone and water breakthrough not much affected by the end effect,
 - wide saturation variation zone at low injection rate (2.6 cm/d) ; there is spontaneous water imbibition, not compensated by a water influx ; water reaches the outlet face well before being produced, after the development of some end effect ; fig. 10. The exchange surface between trapped gas and free gas is more important than earlier.

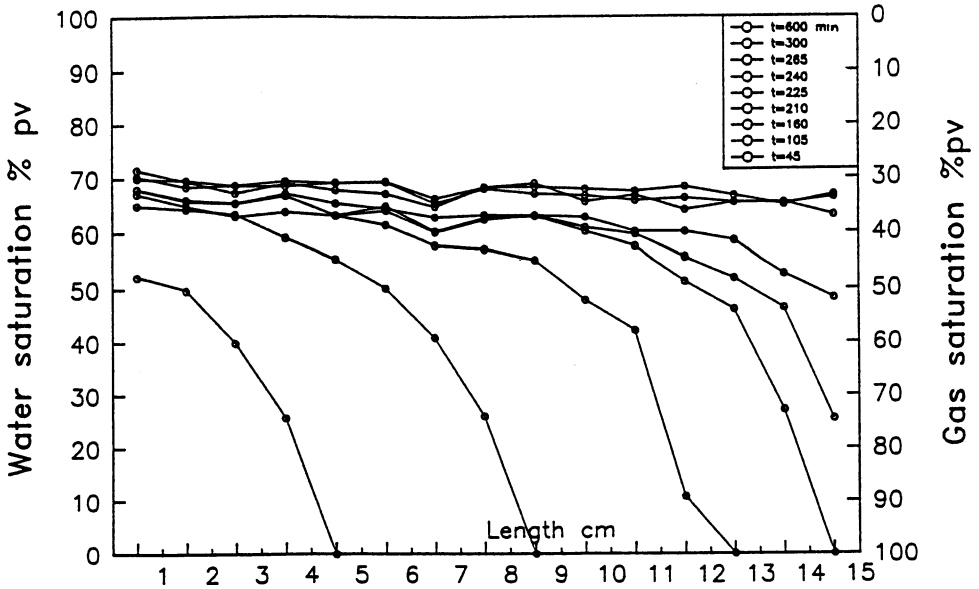


Fig 9 Water gas saturation profiles
High rate Water/air system

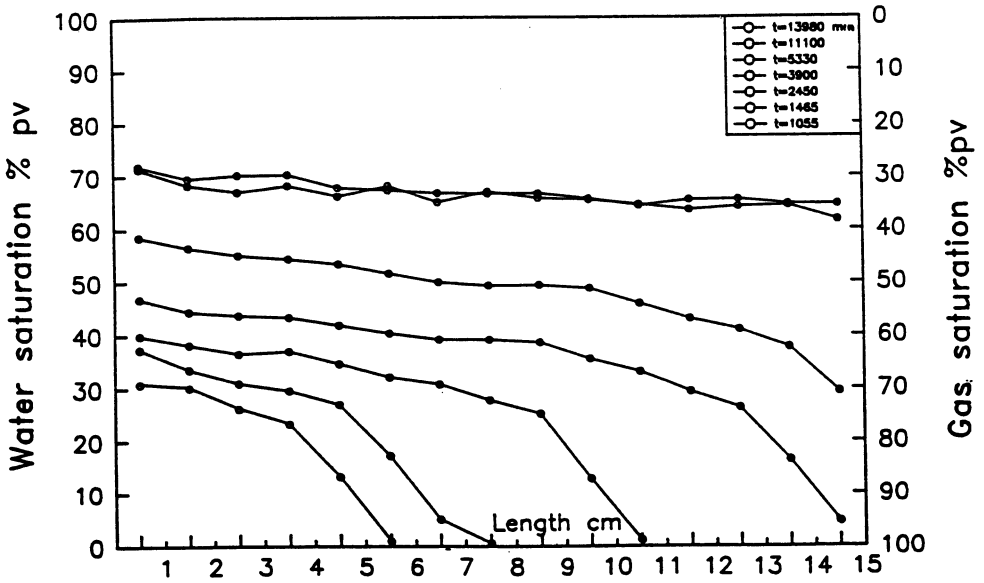


Fig 10 Water gas saturation profiles
Low rate Water/air system

- the residual gas saturations (at water breakthrough) are quite similar, despite the different shapes of saturation profiles during flooding test :

Sgr = 31.6 % at high rate,

Sgr = 30.8 % at low rate,

Sgr = 32.5 % capillary imbibition on annex core.

This suggests that there is no effect of velocity on the diffusion, and therefore we can wonder if the slight lack of equilibrium necessary for the diffusion to start can occur when there is a flow, even very slow.

However, we must mention that at identical conditions, Geffen et al (4) have observed quite important changes of Sgr, from 28.7 % at low rate to 31.7 % at high rate. In bottom hole conditions, this difference becomes negligible ;

- the residual gas saturation changes by no more than 0.5 % V, after injecting 10 V_P over a 60 days period. Without^Pany flow of water, this^P change should have been 3.3 % V, from the previous formulas ; we can conclude that the^P flow of water is causing some perturbation to the diffusion process.

Reservoir conditions experiments result

The residual gas saturations are identical for all experiments :

Sgr = 38.7 % low rate,

Sgr = 37.5 % high rate,

Sgr = 37.5 % capillary imbibition on annex core.

There is no significant change of Sgr after a cumulative injection of 12 V_P. We can therefore conclude that there is no significant diffusion phenomenon in reservoir conditions.

CONCLUSIONS

The diffusion of trapped gas exists in laboratory condition experiments without any liquid forced injection.

When the pressure is increased, this diffusion effect is decreased, following a $\frac{1}{\sqrt{P}}$ relationship.

A flow of liquid disturbs this phenomenon, which can be neglected under reservoir conditions.

Hence, representative Sgr values can be determined by :

- Sgr measurements by waterflooding, after injecting one to two pore volume of water, (practically, this is sufficient to flood all the mobile gas) and at any (P, T) condition, with any sample length, and at any rate. Care should be taken to avoid too large differential pressure and to measure gas saturation at trapping pressure, and also one should keep in mind that connate water saturation has a strong influence,
- Sgr measurements by capillary imbibition before the diffusion period.

We can choose between these two techniques, but the second one is particularly well adapted to low permeability samples.

A good agreement between laboratory measurement and some log determinations on the field has been observed in the case described here.

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NOMENCLATURE

V_S	= solid volume
V_P	= pore volume
V_T	= total volume
A	= section area
L	= length
ΔP	= pressure drop
P_S	= outlet pressure
P_C	= capillary pressure
S_{wi}	= connate water saturation
S_{gr}	= residual gas saturation corresponding to $S_{gi} = 1 - S_{wi}$
S_{grM}	= maximum residual gas saturation corresponding to $S_{gi} = 1$
K_g	= gas permeability
ϕ	= porosity
t	= time
P	= absolute pressure
Q	= injection rate
$\frac{Q}{A\phi (S_{gi} - S_{gr})}$	= frontal velocity

TABLE 1 RESIDUAL GAS SATURATION BY WATER FLOODING

SAMPLE	CORE FLOOD TYPE	LENGTH CM	AREA CM ²	INJECTION RATE CM ³ /H	FRONTAL VELOCITY q	POROSITY %	GAS PERMEABILITY MD	CONNATE WATER SATURATION % PORE VOLUME	RESIDUAL GAS SATURATION % PORE VOLUME AT 1 VP
					$\frac{A \Delta S}{\Delta t}$ CM/DAY				
① UNCONSOLIDATED	HR AC	27,16	18,74	41	255	31,9	3 083	10,7	24,75
	IR AC			7,14	38,5	31,6	3 133	0	24,8
	IR RC			13,5	86,6	31,4	2 955	10,4	26,06
	LR AC			1,024	6,5	30,9	2 360	9,7	25,5
② UNCONSOLIDATED	HR AC	28	18,59	41	223,5	32	4 200	0	26
	LR AC			1,02	6,4	32	4 430	9,91	25,4
	IR RC			13,5	86,7	31,9	4 150	10,3	26,7
	HR AC			40,7	261	31	2 570	9,99	25,1
③ UNCONSOLIDATED	HR AC	56,1	19,6	20,2	105,3	31,5	3 453	0	25,4
	HR AC			20,2	139,4	31,3	3 540	19,8	23,5
	LR AC			1,03	6,2	31,2	3 585	10,3	25,3
	HR AC			20,2	119,8	31,6	3 600	10,2	24,5
	HR RC			20,2	120,5	31,3	3 370	10,1	24,3
④ CONSOLIDATED	HR LC	14,93	43,26	67,5	215,2	29	860	13	27

HR : high rate

AC : ambient conditions $P_f = 5b$ $T^\circ C = 22^\circ C$

LR : low rate

IR : intermediate rate

RC : reservoir conditions $P_f = 156b$ $T^\circ = 60^\circ C$

Frontal velocity

REFERENCES

- 1 - D.B. Mac WHORTER, A.T. COREY and K.M. ADAM.
The Elimination of Trapped Gas from Porous Media by Diffusion.
SOIL SCIENCE, February 1972, Vol. 116 N° 1, p. 18-25.
- 2 - G.L. BLOOMSBURG and A.T. COREY.
Diffusion of Entrapped Air from Porous Media.
Hydrology Papers. Colorado State University Fort Collins Colorado, August 1964 N° 5.
- 3 - K.M. ADAM, G.L. BLOOMSBURG, A.T. COREY.
Diffusion of Trapped Gas from Porous Media.
WATER RESOURCES RESEARCH, Vol. 5, N° 4. August 1969, p. 840, 848.
- 4 - T.M. GEFFEN D.R. PARISH G.W. HAYNES and R.A. MORSE.
Efficiency of Gas Displacement from Porous Media by Liquid Flooding. Trans Aime, Vol. 195, 1952, p. 29-38.
- 5 - D.C. CROWELL, G.W. DEAN, A.G. LOOMIS.
Efficiency of Gas Displacement from a Water-drive Reservoir.
Bureau of Mines Report of investigation 67 35, April 1965.
- 6 - D.L. KATZ, M.W. LEGATSKI, Mr TEK, L. FORRING, R.L. NIELSEN.
How water displaces gas from Porous Media Oil and gas Journal, Jan. 10 1966, p. 55-60.

- 7 - G.L. CHIERICI, G.M. CIUCCI, G. LONG.

Experimental Research of gas Saturation behind the Water Front in Gas Reservoirs Subjected to Water Drive.
World Petroleum Congress Francfort/Main 19th-26th June 1963.

- 8 - B.A. Mac KAY.

Laboratory Studies of Gas Displacement from Sandstone Reservoir Having Strong Water Drive.
APEA Journal 1974.

- 9 - P. BOUSQUIE.

Texture et porosité des roches calcaires.
Thèse Juillet 1979 - PARIS VI.

- 10 - J.R. KYTE, L.A. RAPOPORT

Linear Waterflood Behavior in Water-Wet Porous Media.
Trans Aime, Vol. 213, p 423-426, 1958.

- 11 - C.S. LAND

Calculation of Imbibition Permeability of two Phase and three Phase Flow from Rock Properties.
SPE Journal, p. 149, June 1968.

