LABORATORY MEASUREMENT OF OIL/WATER SATURATIONS BY AN ULTRASONIC TECHNIQUE

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Abstract: This paper describes the measurement of liquid saturations using sound velocity. This technique has already been used for measurement of the concentration of miscible fluids, but the calibration was still a problem for immiscible fluids. In this study, calibration curves had been obtained for various samples of sandstone and carbonates, with oil and water. A Cat-scanner and mass balance on effluent production served as references for saturations. Results show that an approximate linear calibration law can be used in the range of oil saturation 0.2-0.5, for imbibition. In addition, a single calibration curve can be used for all the sections of a homogeneous sample, which enable calibration by using effluent production only. Effects of temperature and pressure on the pure fluids and on the sample were also quantified. In conclusion, sound velocity is an accurate technique for saturation measurements but it requires an efficient thermal regulation.

INTRODUCTION

Several techniques are used in laboratory to measure fluid saturations during laboratory core flood tests. Gamma ray attenuation is commonly used to obtain saturation profiles and electrical conductivity is used for tracer experiments. Computerized tomography (X-rays or NMR) gives 2 and 3-dimensional images of multiphase flow. A technique based on microwave attenuation has been tested in several laboratories but without much success. In complement, we have tested and used for several years another technique based on sound velocity.

In this paper, we present our experimental results concerning this technique and discuss its advantages and drawbacks. The main result is a good accuracy for saturation determination but with a strong dependence on temperature.

BACKGROUND

The technique is based on the variation of sound velocity through the rock sample with the properties of the fluids which saturate the sample. The theory of acoustics of porous media can be found in textbooks (Bourbie, 1986) and in some publications with application to saturation in porous media (Bacri *et al* 1986, Bacri *et al* 1991, Soucemarianadin *et al.* 1989, Hoyos *et al* 1990).

We recall that for a pure fluid, sound velocity V_f is given by:

$$V_f = \sqrt{\frac{E}{\rho}}$$

where ρ is the density and E the elastic constant of the fluid (around 1500 m/s for water and 1300 m/s for oil). For a fluid saturating a porous medium, this equation holds for the longitudinal mode when the sound wavelength is much larger than the mean grain size (Biot's theory). The average density and elastic constant are non-linear functions of the densities and elastic constants of the bulk solid and the liquid. The functions depend on the nature of the coupling (viscous at low frequency and inertial at high frequency) and involves the geometrical properties of the porous medium such as porosity and tortuosity (Bacri *et al* 1991) The velocity in a rock sample saturated with water is of the order of 4000 m/s.

Literature reports experiments with miscible fluids performed at high frequency; and the results agree with Biot's theory for unconsolidated media (Bacri *et al* 1991). For displacement of pure water by ethanol, the error of concentration determination is of the order of 0.2 %.

For two immiscible liquids there is no theory, but Biot's theory has been proved to be still valid when an equivalent fluid is used with the following average properties (Bacri *et al* 1986):

$$E_f^{-1} = S_w E_w^{-1} + S_o E_o^{-1}$$

and

$$\rho_f = S_w\rho_w + S_o\rho_o$$

where the fluids are oil (o) and water (w) with saturations S_w and S_o. Immiscible experiments (Bacri *et al* 1986) have shown a strong hysteresis of sound velocity vs. saturation, between drainage and imbibition. However imbibition was performed without connate water (the medium was 100% saturated with oil before imbibition), an unusual situation in laboratory experiments.

Our purpose was to obtain the calibration curves (sound velocity vs. saturation) for imbibition at laboratory conditions. The effects of pressure and temperature on sound velocity were also measured.

EXPERIMENTS

We will now describe a typical experiment to give an idea of the variations of transit times induced by saturation variations. These variations should be compared with the variations due to pressure and temperature variations, presented in the last part of this paper.

Fluid saturation is deduced from the variation of velocity of the compressional wave (longitudinal mode) by using a simple equipment already described in previous publications (Hoyos *et al* 1990). We used two probes made of several piezoelectric transducers. The probes are located on two opposite sides of the sample. They are made of titanate-zirconate ceramics. Their size is 15mm long, 3mm wide and

3mm thick. The resonance frequency is around 350 kHz, and the spatial resolution reaches 4mm (Soucemarianadin *et al* 1989).

The velocity is calculated from the transit time of a pulse through the sample. Electronic equipments consist of a pulse function generator, a power amplifier, an oscilloscope, a time counter, a switching scanner and an amplifier. This equipment is controlled by a micro computer. For each transducer, the variation Δt of transit time is measured by reference to the transit time t_0, when the sample is fully saturated with water. The transit time is of the order of 10-40 µs and the accuracy of the measurement of the transit time variation is of the order of 1ns.

A typical experiment consists of drainage (fig. 1) followed by imbibition (fig. 2) of a water-wet Vosges sandstone (20cm long with a 4cm diameter), coated with epoxy resin (thickness 2cm). Porosity is 22.9% and permeability 173mD. The wetting fluid is a 15 % NaCl aqueous solution and the nonwetting fluid is a refined oil with viscosity 1.5×10^{-3} Pl at 21°C (Soltrol).

Figs. 1 and 2 present the variations of transit time Δt during drainage and imbibition as a function of time for four transducers At end of drainage the four transducers show a Δt of around 500 ns. At end of imbibition, the common value is around 400ns. Figs. 1 and 2 show clearly the passage of the front of injected water, reaching first the transducer number 1 and travelling through the sample.

With a resolution of 1ns, we can expect an accuracy better than 1% on saturation. However, we need an accurate and reproducible calibration.

CALIBRATION

A Cat-Scanner is used as a reference with an accuracy of about 2% saturation. First, it was made sure that there was no rearrangement when the flow was stopped and the sample moved for scanner measurement. Then the saturation was

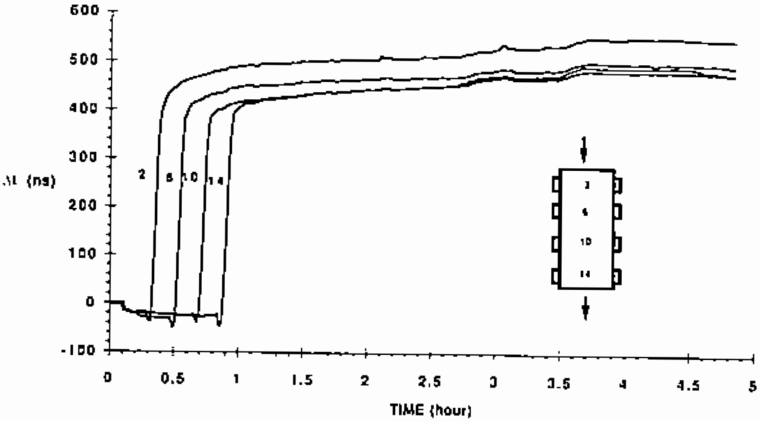

FIGURE 1 Variation of transit time during drainage in a Vosges sandstone.

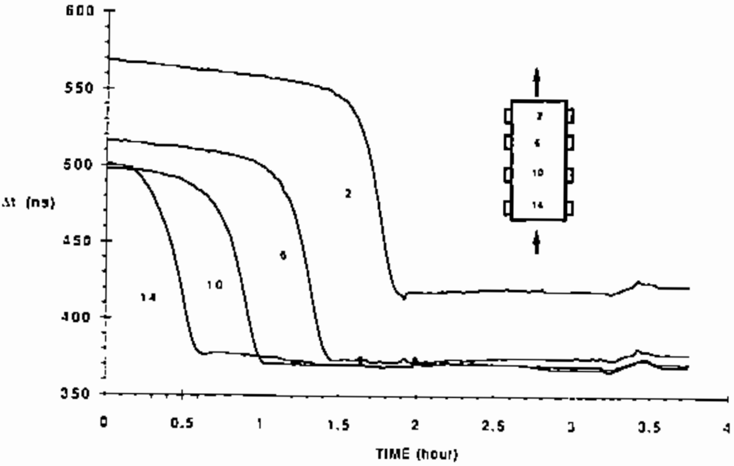

FIGURE 2. Variation of transit time during imbibition in a Vosges sandstone.

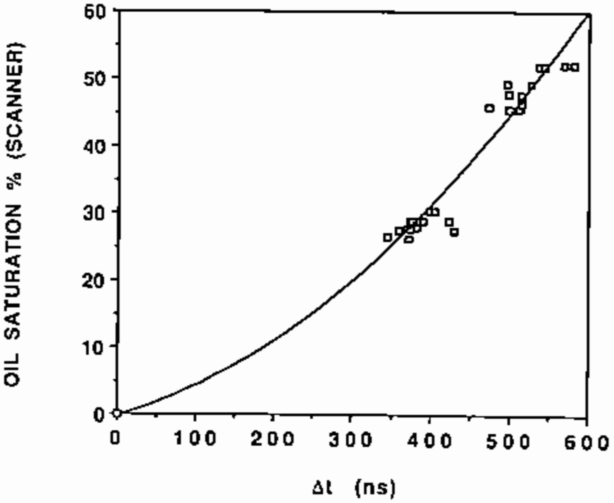

FIGURE 3. Calibration curve for a Vosges sandstone. Transit time variations vs. scanner saturations.

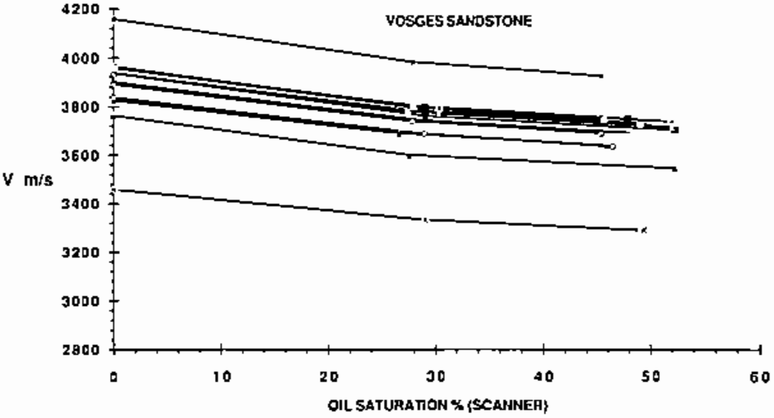

FIGURE 4 Calibration curve for a Vosges sandstone. Absolute velocity vs. scanner saturations.

measured at different locations near the 15 transducers at end of drainage and at end of imbibition.

Figure 3 shows the variation of transit time for several transducers at different saturations. A large scatter between the different transducers is observed. In order to allow the comparison with other experiments, the sound velocity through the sample was calculated by subtracting the transit time trough the epoxy coating (19.450µs). The results are shown in figure 4. A difference in the initial transit time t_0 caused by porosity heterogeneities was found. This effect can be removed by using the relative sound velocity for each transducer As predicted by Biot's theory, the calibration curve has a curvature. However, without intermediate measurements during drainage and imbibition, the possibility of hysteresis cannot be excluded. Thus, the calibration curve is used only for imbibition experiments. Within the accuracy of the scanner saturations, a linear approximation can be used in the range $20<S_0<50$, (fig. 5).

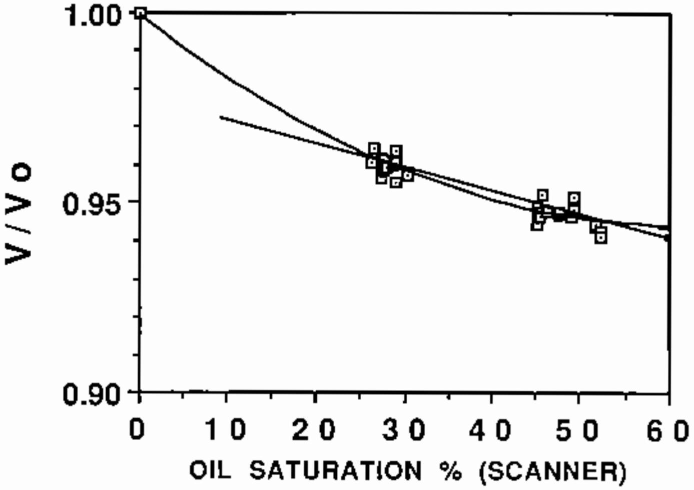

FIGURE 5 Calibration curve for a Vosges sandstone. Relative velocity vs. scanner saturations.

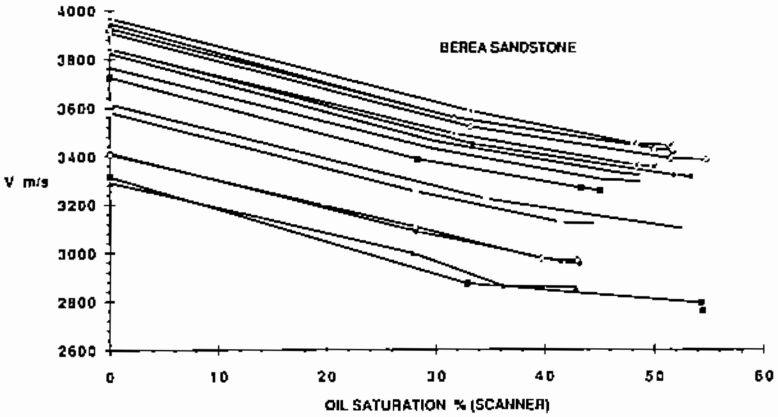

FIGURE 6 Calibration curve for a Berea sandstone. Absolute velocity vs. scanner saturations.

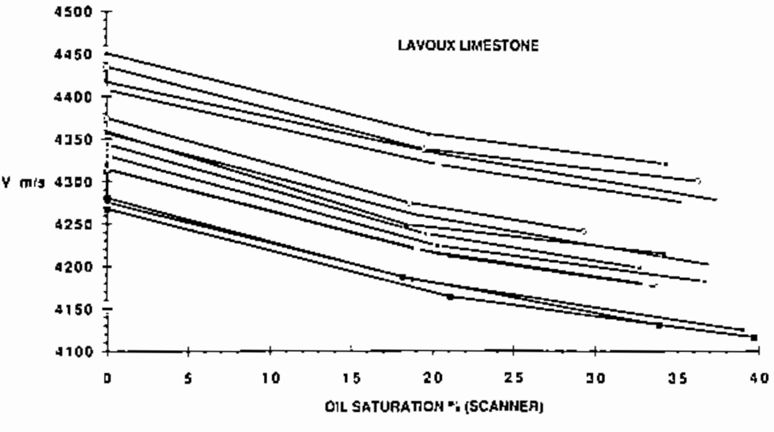

FIGURE 7 Calibration curve for a Lavoux limestone Absolute velocity vs. scanner saturations.

For comparison, Figs. 6 and 7 give the sound velocities obtained during displacements in two other samples, a Berea sandstone (porosity 21% and permeability 151 mD) and a Lavoux limestone 26.9 and 163 mD). We observe first that all the curves are roughly parallel, which leads to a small scatter of the relative sound velocity. In addition, a larger transit time variation is noted for the Berea than for the limestone.

For a relatively homogeneous sample, the same law can be used for all the transducers, when the relative sound velocity is used. Consequently, an accurate mass balance on the effluent at end of displacement can be used for calibration, without the need of another tool for reference measurement. This calibration method is illustrated on the Lavoux limestone (fig.7). A linear relation is assumed between the relative sound velocity of transducer number i and local saturation: $V(i)/V_0 = aS_0(i) + b$ (in the range $0.2 < S_0 < 0.5$, for instance). Assuming that each of the 14 transducers measures the same volume of porous medium, the average saturation $<S_0>$ deduced from the effluent volume is given by the sum over all the local saturations:

$$a <S_0> = \frac{1}{n} \sum_{i=1}^{n} \frac{V(i)}{V_0} - b$$

The two unknowns a and b are determined if we have two equations, i.e. two effluent measurements. For this purpose, the end of drainage and the end of imbibition were used. The result is close to the result of scanner calibration (fig. 8). The previous formula can be easily improved to account for irregular spacing of the transducers. This method can also be applied to any non-linear law, but with the restriction of equal number of unknowns and effluent measurements.

DISCUSSION

We have shown that sound velocity is sensitive to a small variation in saturation, less than 1% (for the Berea sample, 50% saturation change corresponds to a Δt of 400ns which is measured with a resolution of 1ns). However, this sensitivity

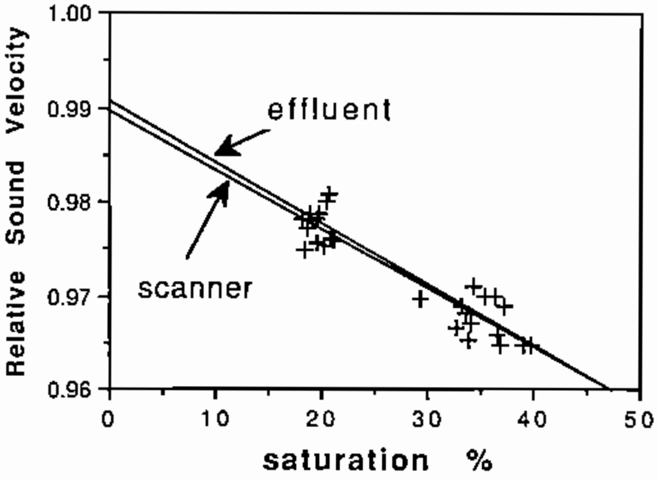

FIGURE 8 Calibration curve for a Lavoux limestone during imbibition. Comparison between scanner and effluent production measurements for saturation reference.

does not mean accuracy because of possible errors due, for instance, to temperature and pressure effects on sound velocity. Both these effects have been studied at laboratory conditions.

Effect of temperature has been studied on the previously described Vosges sandstone at end of imbibition (S_0=0.3). Without any flow, the temperature of the sample was increased from 21.7 °C to 25.8 °C. The response of 4 transducers is shown in fig. 9. Variation of transit time is about 360ns, which gives 90ns per degree. The time constant of a few hours corresponds to the thermal inertia of the sample. After 17 hours, the temperature is set to its previous value and the sound velocity recovered its initial value after a few hours (fig. 9). This effect corresponds to a variation of Δt of +90ns for +1°C. For comparison, the pure fluids in a 5cm diameter cylinder had a variation of -30ns for water and +130ns for oil (for +1°C).

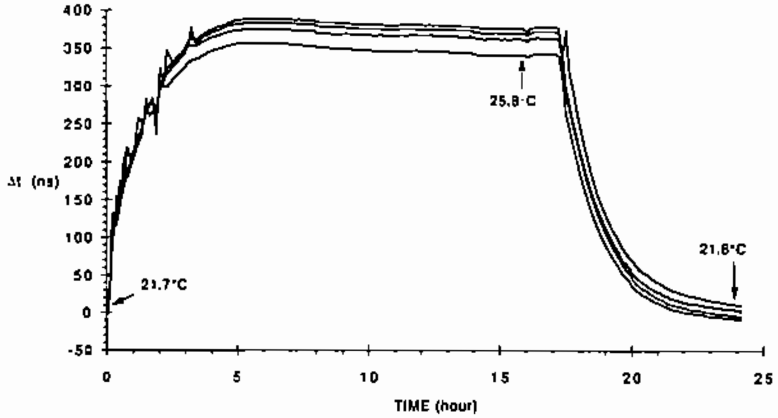

FIGURE 9 Effect of temperature on transit time for a Vosges sandstone saturated with water

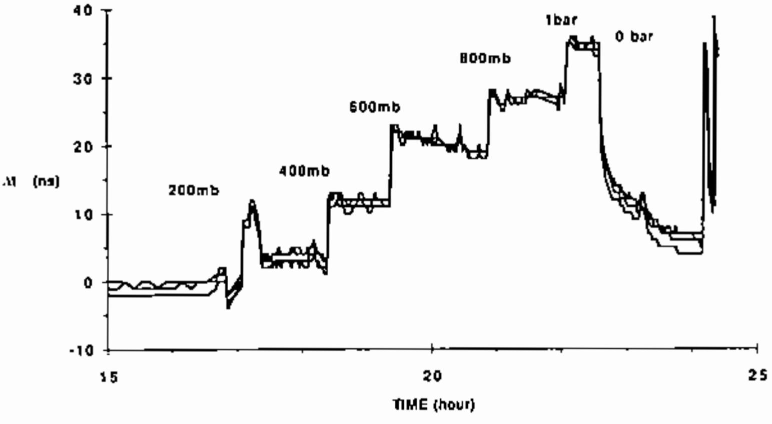

FIGURE 10 Effect of pressure on transit time for a Vosges sandstone saturated with water.

The effect of pressure on the same sample saturated with brine is shown in figure 10. Pressure was applied on the liquid only and was increased in steps up to 1 bar. We observed a linear response of transit time to pressure of the order of 35ns at 1 bar (10^5Pa). The response to an increase of pressure is instantaneous. However, a relaxation is observed when the pressure is decreased, with a time constant of about 1 hour. This time constant depends on the duration of the applied pressure. During single-phase flow, the same law between pressure drop and variation of Δt during flow was measured. For pure liquids at 1 bar, the variation is 15ns for Soltrol and is negligible for water (in a 5cm diameter cylinder). With a sample porosity of 30% these values led to a contribution of less than 5ns for the fluids. Consequently, the main contribution is due to the solid.

CONCLUSIONS

Use of sound velocity for liquid saturation measurement has several advantages, compared to gamma-ray, for instance:

- accuracy and high speed of acquisition.
- low cost
- no safety hazards
- spatial resolution of a few mm.
- possibility of use at high temperature and pressure.

We have shown that the effluent production can be used for calibration when the sample is homogeneous and there is no need for reference measurements such as Cat-scanner or gamma-ray.

However, the main drawbacks are:

- so far,limitation to liquids (strong attenuation with gas)
- the need for temperature regulation, comparable to electrical conductivity measurements.

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