Laboratory study of the influence of changing the injection rate on P-wave velocities and water saturation in a Limestone

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SUMMARY

Forced imbibition was performed in a Limestone Savonnieres by injecting water into a dry sample. The injection was monitored with X-ray Computed Tomography (CT) and active ultrasonic measurements so that the time-space distribution of the invading fluid could be simultaneously observed in CT images and quantified through measuring P-wave velocities and water saturation.

The CT scans allowed us to observe a water front advancing away from the area of injection and estimate saturation. Through the evolution of P-wave velocities, we observed a strong influence on the acoustic response with the presence of water and with the changing of injection rates. The approaching of the water front to the monitored position decreased P-wave velocities while the saturation increased continuously. The P-wave velocities decrease occurred for a short period of time and was followed by a sharp increase which happens when the fluid front crossed the monitored position. Decreasing injection rate decreased P-wave velocities and saturation. Increasing injection rate, increased P-wave velocities and saturation, sharply and for a short period of time followed by a slight decrease for P-wave velocities and a continuous increase.

Our experimental data confirms how sensitive acoustic waves are to the presence of water and that changing injection rates promote considerable fluid distribution that is drastically reflected in the acoustic velocities.

Key words: Limestone, Imbibition, Acoustic Monitoring, X-ray Computed Tomography, Rock Physics.

INTRODUCTION

Quantification of fluid flow through porous media is an essential part of hydrocarbon recovery and reservoir characterization. In particular, the controlled replacement of one fluid by another is a common procedure in order to stimulate reservoir performance, for example, recovering oil by means of water flooding (Craft *et al.*, 1991). When injecting fluids in a rock, acoustic *data* can indicate the presence of fluids: the amplitude, wavelength and arrival time of the P-waves change with the injection of water (as shown by our data in Figure 1).

The presence of fluids also results in a change of the elastic properties of a rock, reflecting the magnitude of solid/fluid interaction (Guéguen *et al.*, 1994). More particularly, seismic wave velocities and attenuation are affected by the degree of saturation and spatial distribution of fluids (Müller *et al.*, 2010). Several laboratorial experiments dealing with fluid injection to study acoustic response by active monitoring (Monsen *et al.*, 2005) and the time-space fluid distribution with X-ray CT (Akin *et al.*, 2000) have been performed extensively. But so far, very few used the simultaneous application of an ultrasonic measuring technique and an image processing technique (Lebedev *et al.* 2009).

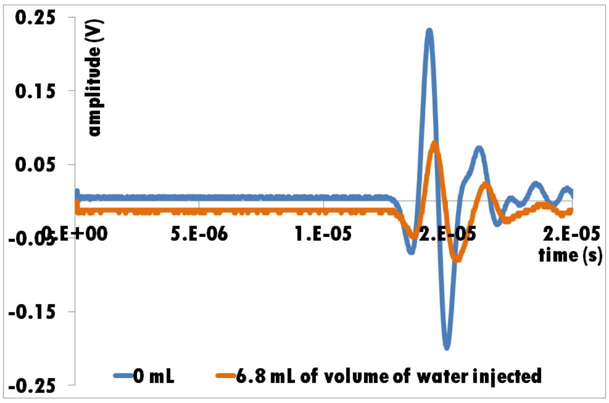

Figure 1. Waveforms for the P-waves picked during this experiment: before injection (blue line) and after injecting 8.4 mL of volume of water (orange line). Note the decrease of wave-amplitude and increase of wavelength.

It is our purpose to quantify fluid displacement through measuring acoustic wave velocities and water saturation while providing an image representative of the fluid distribution during injection and present a more complete and comprehensive analysis of solid/fluid interaction when the injection rate at which the wetting fluid is introduced changes during the forced imbibition.

EXPERIMENTAL SETUP AND METHOD

Water was forced with an injection pump to displace air in a Limestone Savonnieres which main characteristics are presented in Table 1. The experimental setup consisted of a signal source, an oscilloscope and an injection pump. The injection was vertical and the sample was laterally covered by epoxy with two plastic bases glued to the bases of the sample (to hold the sample upright) with an open end at the top (Figure 2). The experiment was performed at room temperature and atmospheric pressure and consisted of the following steps:

1. Initial injection at 2 mL/h during approximately 4 hours (up to 7.9 mL of volume of water injected);
2. We decreased injection rate to 0.2 mL/h and we kept it constant for 15 hours;
3. When we reached 10.7 mL of volume of water injected, we increased injection rate back to 2 mL/h for the next 3 hours.

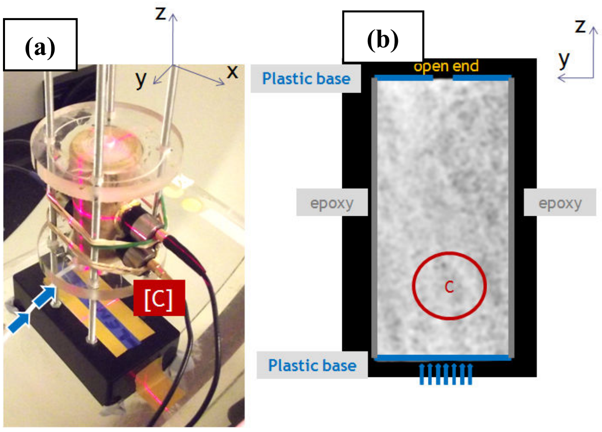

Figure 2. (a) Sample connected to the piezoelectric transducers (central frequency: 1 MHz). We only present the results of the pair of transducers in position C, closer to the area of injection. (b) Typical CT scan of our sample. Blue arrows represent the direction of injection and the red circle, the area covered by the transducer.

LIMESTONE SAVONNIERES	
Length (cm)	7.81
Diameter (cm)	3.84
Porosity (%)	26.5
Pore Volume (mL)	23.9
Permeability (mD)	91.5
Main colour	Beige

Table 1. Main characteristics of the Limestone Savonnieres.

P-waves were picked by piezoelectric transducers placed on a position close to the area of injection (position C, Figure 2) while the sample was scanned always along the same axial plan so that to a value of P-wave velocities we could match a value of water saturation. P-wave velocities were calculated through the first-break picking of the output signal given by the oscilloscope and (after image processing) the CT images provided us a visual display of the fluid front (Figure 3).

Through the CT images, we were also able to calculate water saturation. Each pixel of the CT images has a "CT number" that is directly related to the density of the scanned sample. The consecutive scanned images reflect the presence of water in the sample by an increase of the CT number (i. e., the area filled with water becomes "whiter"). For each pixel, the water saturation $S_{w,}$ for a specific moment of the experiment, is given by $S_w=[CT(w)-CT(dry)]/[P\times 1000]$, where P is the porosity of the sample (Toms-Stewart *et al.*, 2009). (Note that the calculated water saturation is "local", related to the area monitored by the transducers.)

RESULTS AND DISCUSSION

The evolution of P-wave velocities with volume of water injected is shown in Figure 4 and the water saturation in Figure 5. Figure 3 represents a sequence of CT digitalized images for the first part of the experiment (during the initial injection at 2 mL/h) where we can see the position of the fluid front relative to the area covered by the transducers.

When the water front approached the monitored area, at 2.1 mL (Figure 3-B), P-wave velocities started decreasing. This decrease is related to the increase of bulk density (decrease of local porosity). At 3.3 mL of volume of water injected (Figure 3-C), P-wave velocities and water saturation started increasing as the fluid front crossed the monitored area. While the position of the fluid front changed drastically the evolution of acoustic velocities, the saturation increased continuously.

We can see the influence of changing injection rates in the acoustic response and evolution of water saturation:

1. Decrease of P-wave velocities for 3 hours when we decreased injection rate, followed by an increase from 3377 m/s to 3403 m/s, which remained constant for the next 10 hours at the injection rate of 0.2 mL/h (Figure 4);
2. Increase of P-wave velocities when we increased injection rate back to 2 mL/h, from 3403 m/s to 3424m/s in 1h30, followed by a slight decrease to the final P-wave velocity of 3419 m/s (Figure 4).
3. Decrease of water saturation with the decrease of injection rate, from 59 % to 45 % (which also remained constant for the next 10 hours). When we increased injection rate, the saturation increased immediately to 58 %, followed by a continuous increase to 72 % (Figure 5).

The decrease of P-wave velocities when we decreased injection rate seems to be connected to the partially saturated conditions of the sample (58 %). This means that locally there were still 42 % of pores filled with air that was "free" to expand and move due to decrease of the pore pressure that was no longer forced by the higher injection rate. The redistribution of fluid induced by decreasing the injection rate is followed by stabilization: the value of P-wave velocities and saturation remained constant for the last 10 hours at the injection rate of 0.2 mL/h. When we increased injection rate back to 2 mL/h, the fluid redistribution is reflected in the immediate increase of saturation and P-wave velocities.

The presented method enables us to relate simultaneously acoustic velocities, saturation and localization of fluid front during laboratory experiments dealing with fluid injection. We conclude with this experiment that changing the injection rate has a significant impact in the acoustic response and saturation. More particularly: (1) a decrease of P-wave velocities and water saturation with decreasing injection rate and (2) an increase of P-wave velocities and water saturation after increasing injection rate.

CONCLUSIONS

It is clear from our experiment that acoustic wave velocities are very sensitive to the change of injection rates. This change implies a reorganization of fluid that it is reflected on the evolution of saturation and more drastically in the acoustic response. The influence of fluid distribution in acoustic velocities has been observed experimentally (Cadoret *et al.*, 1995) but this is the first time it is experimentally related to

changing the injection rate of the invading fluid.
Our previous work on sandstones (Lopes and Lebedev, 2011), has shown also a clear a dependence of the acoustic response and water saturation evolution with the changing of the injection rate, though in sandstones the decrease and increase of P-wave velocities was higher in absolute value and it was more immediate (faster) which is consistent with a less stiff matrix (when compared to limestones). More work will be developed to study the influence of changing the injection rate in other samples of sandstones and limestones, with different porosities and permeabilities.

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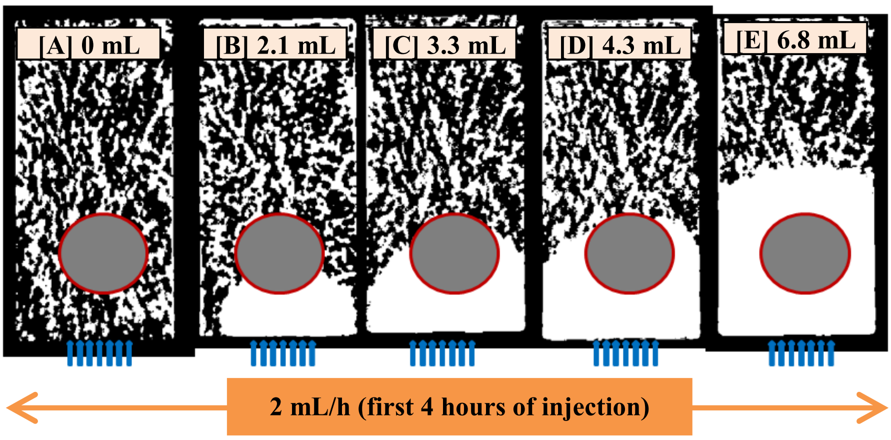

Figure 3. Digitalized CT images for the first 4 hours of injection. Red circles represent the area covered by the transducers and blue arrows, the direction of injection. [A] When we started injection; [B] after injecting 2.1 mL of water, the fluid front approached the monitored area and P-wave velocities started decreasing; [C] after injecting 3.3 mL of water, P-wave velocities and water saturation started increasing as the fluid front crossed the monitored area; [D] after 4.3 mL of water injected and [E] at 6.8 mL of water injected, the fluid front passed the monitored area.

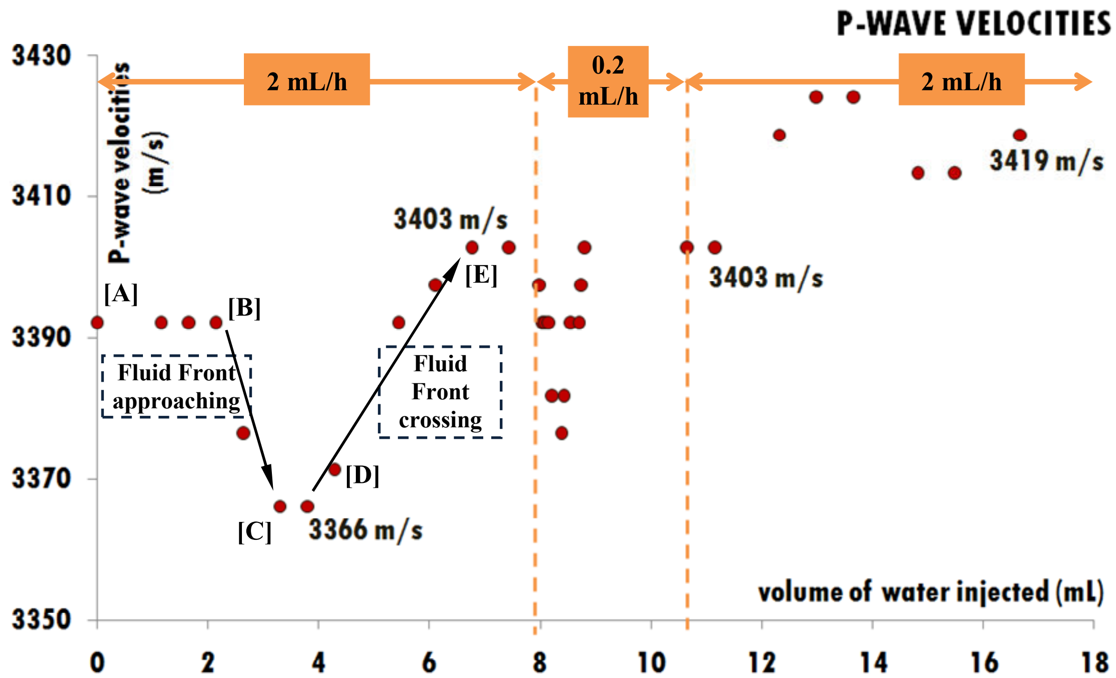

Figure 4. P-wave velocities with volume of water injected. Dashed lines represent the moments when we decreased injection rate, at 7.9 mL of volume of water injected, and when we increased injection rate at 10.7 mL. [A] to [E] represent the moments depicted in Figure 3 and 5. Note the influence of the fluid front on the acoustic response: decrease when it is approaching the monitored area and increase when it is crossing it.

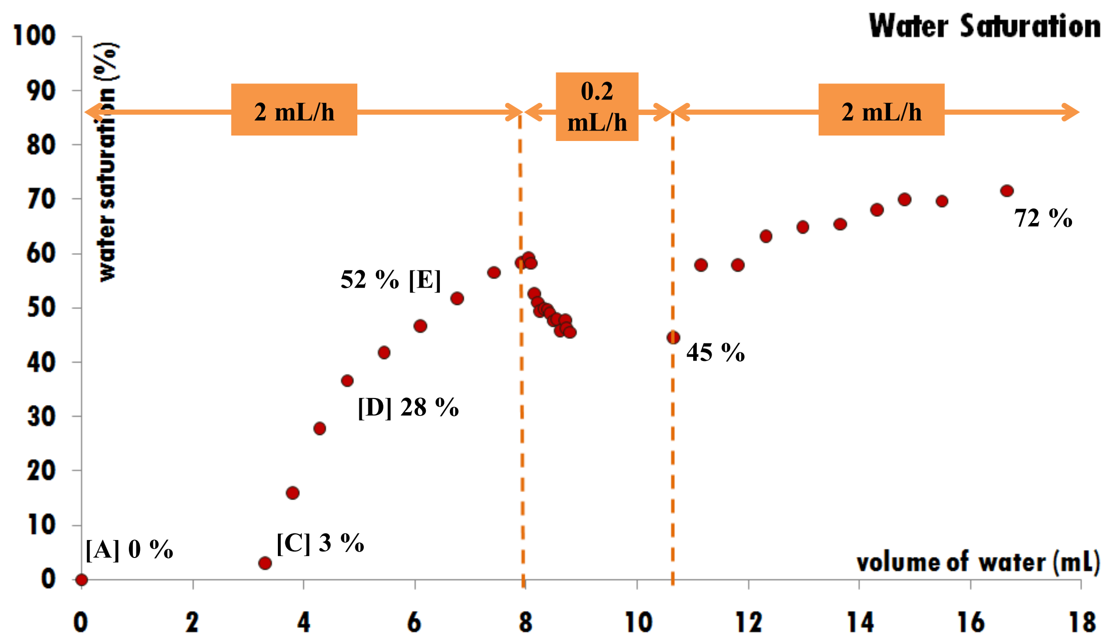

Figure 5. Water saturation with volume of water injected. Dashed lines represent the moments when we decreased and increased injection rate at 7.9 mL and 10.7 mL of volume of water injected, respectively. [A] to [E] represent the moments depicted in Figure 3 and 4. Note that, unlike the acoustic velocities, the water saturation increases continuously with the advancing of the fluid front.