Ultrasonic Technique on Fluid Saturation in Porous Media

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Abstract: Phase behavior of hydrocarbon fluids is closely related to porous media. However, there are many limitations of current detection techniques. Therefore, it is very urgent to find a suitable method to solve this problem. In this paper, based on the brine and three natural cores from Jilin oilfield, the relations of the interval transit time and fluid saturation of these cores both in brine/air system and kerosene/air system were measured, and the difference of these relations during the process of displacement, imbibition and air drying were compared and analyzed. Results show that the ultrasonic technique is a potential method to invert fluid saturation in porous media.

Keywords: Ultrasonic technique, fluid saturation, porous media, Phase behavior, interval transit time.

1. INTRODUCTION

Phase behavior is vital to the development and management of reservoirs and affects all aspects of petroleum exploitation and production [1]. So far, there are numerous studies and achievements in this field. [1, 2] However, most of the results are based on conventional PVT methods [1, 2] which means that the physical parameters and phase behavior of the fluids have nothing to do with the porous media of the reservoir.

Undoubtedly, the effect of porous media on fluid distribution cannot be ignored because there are some interfacial phenomena like the wettability, absorption, capillary forces and interfacial tension between the fluids and porous media [1-5]. All these phenomena could have a significant influence on distribution and seepages of fluids. In this respect, the quantitative, transient and spatial distribution of the fluid saturation during coreflooding is one of the classic problems in the development of oil and gas fields. Consequently, it is vital to study transport characteristics in porous media, such as the mixing of miscible fluids or two phase flows [1, 2].

In recent years, microwave transmission technique [1, 2], gamma ray absorption techniques, and computerized tomography with either X-rays or nuclear magnetic resonance (NMR) have been used for measurements of saturation profiles and imaging multiphase flows in porous media during coreflooding [1-5]. These modern techniques, however, may be less and less suitable for fast flow experiments and large samples. What's worse, they are of little use for studies at temperature and pressure conditions that require a metal coating. By contrast, acoustic imaging can accommodate a wide range of sample coatings that are transparent to acoustic waves. In addition, it is less expensive, faster, and there is no requirement of dopant [11, 12].

The investigation of wave propagation in fluid-saturated porous media was pioneered by Frenkel [1], Beranek [2], and Morse [3], and then rigorously developed by Biot [4]. Almost all of the ultrasonic applications in porous media nowadays are developed on the basis of Biot's theory. In 1962, he used a phenomenological approach, that is, a reasoning on the basis of the physics at the macroscopic scale, for deriving the mathematical model that classically described the mechanical properties of a fluid-saturated porous media [5, 6]. Twenty years later, Johnson and Plona [7] discussed the variations of the ultrasonic propagation in the fluid-saturated porous media experimentally. In 1984, Bacri *et al.* [8] measured the velocity changes of miscible displacement process in a pack of glass beads saturated with water/ethanol mixtures of various concentrations, which are in perfect agreement with Biot's theory.

Based on the difference in the ultrasonic velocities in the various liquids saturating the porous media, an automated system for two-dimensional (2D) saturation mappings has been designed by SoucemarlanadIn *et al*. Unlike X-ray shadowgraphs, quantitative fluid saturation data can be obtained, and the flood front can be located. In addition, the motion of viscous fingers can also be reconstructed [11]. In 1990, to accurately determine the complete profile in the entire sample, Bacri *et al.* designed a 3D acoustic scanner, which is very suitable for coreflooding experiments, because it could monitor large samples and is transparent to most core coatings [12]. However, one common deficiency of

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Table 1: Physical Parameters of the Natural Cores

No.	Porosity, %	Density, g/cm^3	Length, cm	Diameter, cm	Quartz, %	Feldspar, %	Cement, %	Mica, %
J1	19.88	2.17	5.02	2.51	70	4	20	6
J2	14.63	2.26	4.99	2.51	65	5	25	5
J3	9.96	2.39	4.55	2.50	55	7	35	3

Table 2: Compositions of the Formation Water

Ion type	Na^+ & K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	sum
Content, mg/l	4072.2	50.5	28.1	4481.6	1049.5	2055.8	11737.7

these two apparatuses is to be depended on the liquid/liquid system such as water and oil.

As is known to all, the local saturation in oil and water has always been one of the basic experimental problems in oil recovery and immiscible flows. However, the interval transit times of the porous media like sandstone saturated with oil or water are close to each other. Consequently, it has been generally accepted that ultrasonic methods are inappropriate for the determination of saturation profiles in porous media [12].

Recently, with the increasing number of applications of gas driving methods like CO_2 flooding, nitrogen flooding, and air flooding in oil and gas reservoirs to enhance oil recovery, and the widespread applications in CO_2 sequestration to protect the environment, more and more attention has been paid to the phase behavior of water/gas and oil/gas system. Unlike water and oil, gas is obviously different in physical properties like density and viscosity. Therefore, in view of the advantages of the ultrasonic technology and the significant difference between gas, water and oil, experiments were conducted to obtain the relationships of the interval transit time and fluid saturations of natural cores during the process of inbibition, air drying and displacement. And then differences between these three kinds of relations were compared and discussed.

2. EXPERIMENTAL DETAILS

2.1. Materials

Natural cores and formation water used in the experiments were from Jilin oilfield in China. To compare the difference in displacement process, imbibition process, and air drying process under normal pressure and temperature (NPT) conditions, kerosene and air were chosen to represent oil and gas, respectively. Table **1** shows the physical properties and thin section analysis of the natural cores. Compositions of the formation water are shown in Table **2**.

2.2. Experimental Apparatus

SCX-II ultrasonic test system was used to measure interval transit time variations of the natural cores when saturated with kerosene, brine, and air, respectively. As is shown in Figure **1**, the key element of the system is the transducer probe (200 kHz, 2cm in diameter). It is assembled at the inlet and outlet of the holder. The sound generator and oscilloscope are Agilent 33220A function/arbitrary waveform generator and Agilent 54622A dual channel oscilloscope, respectively. Besides, it has an ISCO pump, a back pressure pump, a confining pressure tracking system, three transfer vessels, pressure sensors, a core holder, and a liquid meter. The transfer vessels, core holder are placed in an electronic incubator, which could provide a constant temperature.

2.3. Method and Procedure

Under normal pressure and temperature conditions, based on SCX-II ultrasonic test system, interval transit time variations of the natural cores with different saturations of brine/air system and kerosene/air system were obtained during the processes of displacement, imbibition, and air drying. Before the experiment, two end faces of the natural cores were rubbed to ensure good coupling during the ultrasonic measurement. The weight method was used to calculate saturation changes of the natural cores. In addition, the displacement rate was 0.01ml/min; 5MPa was loaded by confining pressure tracking system to obtain good displacement effect during the displacement process. However, to compare with imbibition process and air

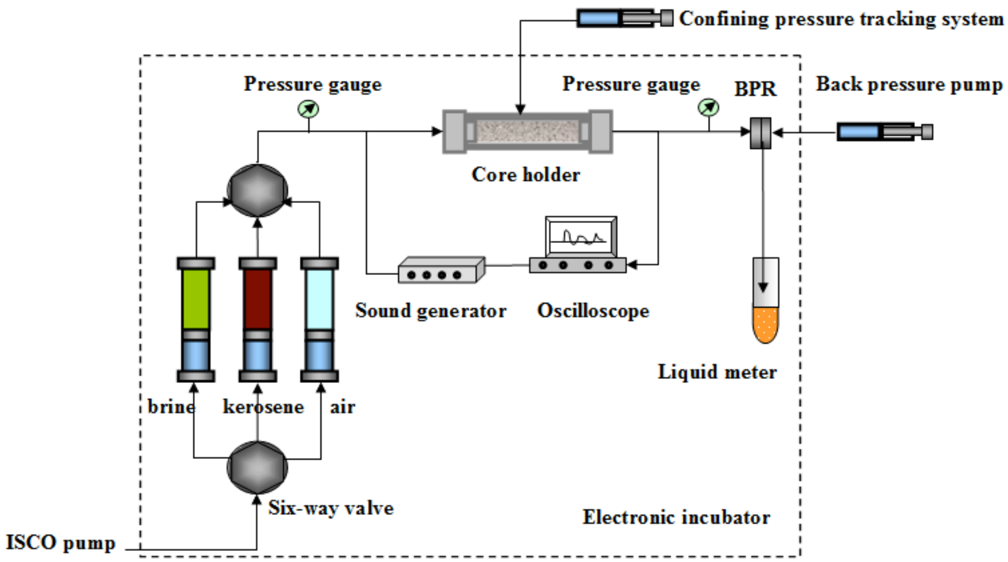

Figure 1: The schematic of SCX-II ultrasonic test system.

drying processes, natural cores were uploaded and weighted after saturation and displacement, and then put back in the holder for testing under NPT conditions, the axial stress should be equal for each test to eliminate the effect of pressure variation on interval transit time variations, and a time interval of 2hours before each test was allowed to make sure the fluids in the cores were relatively in stable conditions.

2.4. Results and Discussion

Considering the difficulties and feasibility of the experiments, kerosene and air were selected to represent oil and gas, respectively. Results showed that the trend of the relationships of the interval transit time and gas saturation in brine/air system and kerosene/air system are very similar with each other. The difference is not very evident, and it mainly lies in specific values because of the difference in density and viscosity between brine and kerosene. In addition, there were numerous researches on the ultrasonic detection in saturation measurement of liquid/liquid system, and the focus of this paper is the relations of interval transit time in gas/liquid system, therefore, in this paper we take brine/air system as an example to study the feasibility analysis of ultrasonic detection in the saturation measurement of gas/oil system in porous media.

2.4.1. Interval Transit Time VS Gas Saturation

Figure **2** compares the relationship of the interval transit time and gas saturation for the three cores during air displacement after brine saturation. It is clear that as gas saturation increases, the interval transit time increases linearly. Correlation coefficients are all higher than 0.98. However, the degree of these changes is closely related to the porosity of the cores. As is shown in Figure **2**, the slopes of these regression equations decrease as porosity increases. It indicates that for the same gas saturation, the higher the porosity, the longer the ultrasonic wave takes in the cores and the smaller the variation scope. In addition, a portion of the brine cannot be displaced because of the irreducible water saturation exists; the effect increases as porosity decreases in the natural cores, which is a significant difference from the conventional PVT cell.

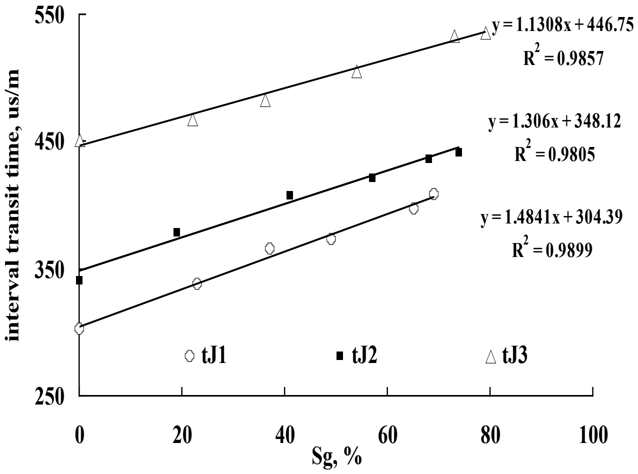

Figure 2: The interval transit time VS gas saturation.

2.4.2. Interval Transit Time VS Porosity

Figure **3** compares the relationship of the interval transit time and porosity of the natural core J2 fully saturated with oil, brine and air, respectively. Obviously, the higher the porosity is, the slower the ultrasonic wave propagates, and basically in accordance with the linear relation. It is believed that the differences in the bulk modulus among the matrix of the natural cores, and the oil, brine or air filled in the porosity are the main reason. Generally speaking, bulk modulus of the quartz is about 40GPa, while bulk modulus of oil, brine, and gas is about 0.1 to 10GPa, 2GPa, and 0.1 to 0.2GPa, respectively. As porosity increases, the portion of matrix decreases while fillings like oil, brine, and gas increases. At the same time, compared with the declination of the bulk modulus of the whole natural cores, density of the natural cores decreases slightly. It means that ultrasonic velocity decreases according to the equation of longitudinal wave velocity. Similarly, as is shown in Figure **3**, ultrasonic wave propagates faster in the cores saturated with oil, followed by the cores saturated with brine and then the cores saturated with air.

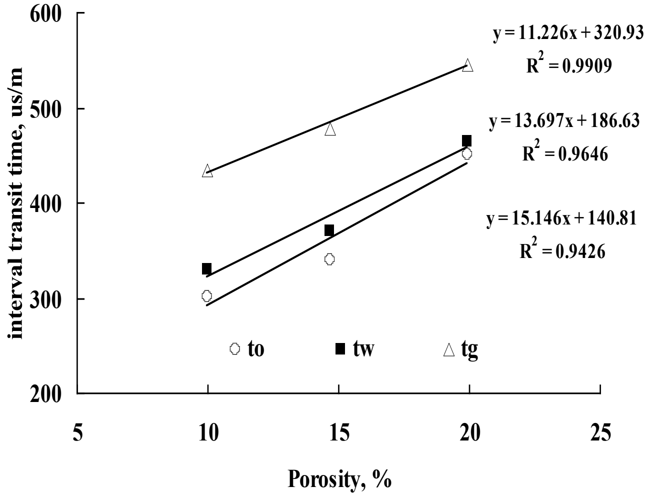

Figure 3: The interval transit time VS porosity.

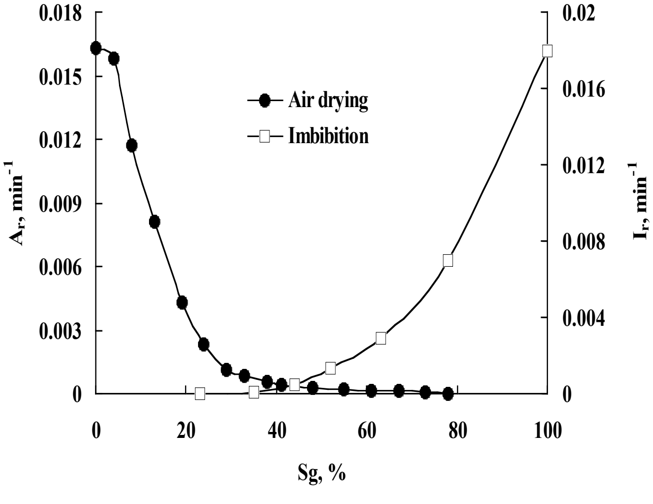

Figure 4: Imbibition rate and air drying rate VS gas saturation.

2.4.3. Gas Saturation VS Imbibition Rate & Air Drying Rate

Figure **4** shows the brine imbibition and air drying curves of the cores J2. Apparently, at the beginning of the imbibition process, the imbibition rate is significantly fast. However, as time increases, the rate decreases rapidly and then keeps on at a very low steady rate, while for the air drying process, there is an obvious smooth transition section. The main mass transfer process is evaporation in the air-water interface and fluids migration in the capillaries.

2.4.5. Displacement VS Imbibition VS Air Drying

Figure **5** compares the change in the interval transit time for the core J2 during the processes of air displacement, brine imbibition, and air drying. It is obvious that the interval transit time of the natural cores is not only related to gas saturation, but also to the order of saturation and fluid distribution.

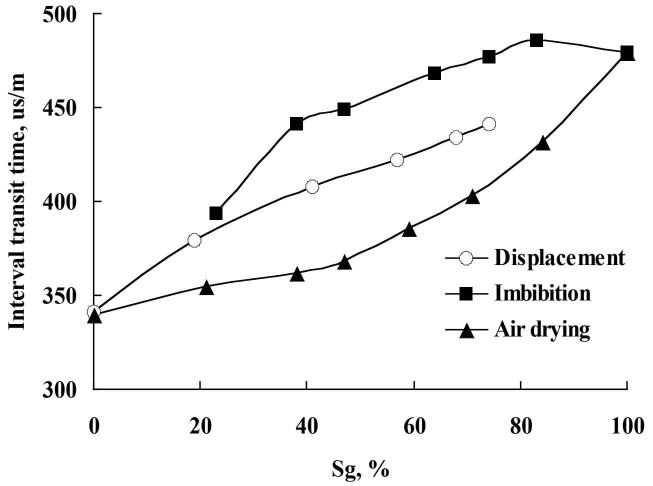

Figure 5: Displacement and imbibition and air drying VS interval transit time.

For the air drying process, the decrease in brine saturation begins from the surface of the core. And most evaporation occurs in the micropores, where brine has little effect on rock elasticity. Consequently, interval transit time changes slightly. After about 40% brine evaporation has taken place, gas begins to enter into the fine pores, where the brine saturation influences the bulk modulus greatly. As a result, interval transit time increases sharply in this region.

For imbibition process, in its initial stage, the brine imbibition rate is very high. As brine saturation increases in the natural core, interval transit time increases from 479us/m to 486us/m. It is indicated that stiffness variation is the reason for the time difference.

Specifically, elastic modulus and velocity of the cores would decrease sharply when the completely dry sample begin to absorb brines. For one thing, the matrix would be softened by active fluid like brine, then bulk modulus decreases significantly and ultrasonic velocity decreases greatly. For another, cementation of the rock particles would be weaker and stiffness of the cores would decrease because of the entering and lubrication of brines, therefore, bulk modulus and ultrasonic velocity would decrease correspondingly. After that, imbibition rate declines to a very low value and brine saturation varies from about 15% to 60%, interval transit time changes slightly because the stiffness of the rock changes slightly. While brine saturation increases from 60% to 80%, interval transit time decreases sharply. The reason is that brine has become the continuous phase of the pores instead of the gas, and macropores of the rock have been saturated while fine pores begin to saturate with brine. Based on the theory of Kauster and Toksoz, ultrasonic velocity is closely related to the stiffness of the fine pores, and the increase of the rock stiffness would greatly increase the ultrasonic velocity of the cores [9, 10].

3. CONCLUSIONS

Interval transit time of three natural cores during the process of displacement, imbibition and air drying both in oil/air and brine/air system was measured by SCX-II ultrasonic test system under NPT conditions. The change of this essential parameter with the increase of air saturation in the natural cores is obtained.

Firstly, interval transit time is closely related to the porosity of the natural cores, the higher the porosity is, the longer the ultrasonic wave propagates and the smaller the variation scope is.

In addition, for the same gas saturation, interval transit times during the process of displacement, brine and air drying are varied greatly. It is believed that the order of saturation and fluid distribution are the main reasons.

Finally, for the physical simulation of fluid saturation in the natural cores, ultrasonic detection is maybe a great method to solve the existing problems like high cost of the saturation detection, poor adaptability in large sample detection, and hard to simulate fluid saturation distribution in porous media under high pressure and high temperature conditions.

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