EFFECT OF FLUID CHARACTERISTICS AND FLOW MECHANISM ON ARCHIE SATURATION EXPONENT

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ABSTRACT

Water saturation determination from wireline resistivity log data depends on measurements of the resistivity index on core samples using Archie's equation. The only variables in Archie's equation are water saturation and rock resistivity, and it is assumed that the relationship is independent of the flow displacement mechanism. This paper reports an experimental investigation of the influence of flow injection rate and the viscosity ratio between the displaced and the displacing phases on the Archie saturation exponent. Resistivity index measurements were carried out by the continuous injection technique. The results show that the saturation exponent is a function of the displacement mechanism and fluids characteristics, and that different resistivity-saturation relationships can be obtained for a given sample under different experimental conditions. Because errors in the evaluation of saturation exponent can give rise to serious errors in the estimation of hydrocarbon saturations, it is concluded that the determination of the saturation exponent requires particular care, and that fluids characteristics and the desaturation method should be carefully selected whenever resistivity index measurements are performed.

INTRODUCTION

Water saturation is commonly determined from electric well logs used the second Archie equation[1] , $I = Sw^{-n} = R_t / R_o$. This equation is empirically based. The Archie's parameters are usually obtained from laboratory measurements on core samples. It is assumed that the saturation is distributed uniformly throughout the sample, and that the saturation exponent n is constant over the saturation range. However, many cases are encountered where the resistivity index (I) shows a non-linear relationship with brine saturation (Sw) on a logarithmic plot. Wettability, microporosity and capillary effects are the main factors which influence this nonlinear behavior. The experimental procedure and especially the selection of injection rates and viscosity ratios for the continuous injection technique may have an important influence on the nonlinearity of logarithmic I versus Sw plots.

If an unsuitable choice of fluid and/or desaturation procedure is used in resistivity index measurements, a non-uniform saturation distribution may result and hence an invalid value of saturation exponent may be obtained. The influence of injection rate and viscosity ratio on I versus Sw relationships has received little attention in the past, probably on account of the time and cost involved in such experiments. However, unreliable values of saturation exponent can result in large errors in the determination of hydrocarbons in place, as described by de Waal[2] .

Generally, the fluid distribution in a porous medium is a function of rock type, pore structure characteristics, wettability, fluid properties, stress, rate of injection of displacing fluid, and desaturation history. The pore structure also affects the profile of the displacing fluid front which in turn modifies the fluid distribution behind it and hence the resistivity values (Grattoni and Dawe)[3].

LITERATURE REVIEW

Various techniques have been developed to measure the electrical resistivity of rocks partially saturated with brine. The porous plate method, the centrifuge method and the

continuous injection method are those currently used in the oil industry. Of these, the most recently developed is continuous injection, which is powerful, accurate and rapid, and provides a continuous curve of I versus Sw rather than a limited number of points[2]. In this technique oil is injected at a constant rate and fixed viscosity ratio to displace brine. It has the advantage that experimental error can be minimized by automation of the measurement procedure and measurements can be performed under effective reservoir stress.

Maerefat et al.[5] used the porous plate method to obtain uniform desaturation and a uniform I versus Sw relation, and showed that it is essential to allow sufficient time to ensure homogeneous saturation. It is believed that at capillary and electrical equilibrium a uniform saturation distribution can be achieved with the porous plate technique, but small scale heterogeneity can cause non-linearity even after this equilibrium is achieved[6]. Lewis et al.[7], applying the continuous injection technique, initially used low injection rates to minimize fingering, then changed to high rates to minimise capillary end effects; they also recommended the use of the 4-electrode system which is not affected by contact resistance. They used samples of high porosity and high permeability, and concluded that capillary end effects and viscous fingering cause the non-linearity of the I versus Sw log-log plot[7].

This nonlinearity may be due to (1) static causes (a vertical, high permeability sample) or (2) dynamic causes (when oil invasion takes place at an end face, the oil saturation profile shows a front moving toward the outlet[18] during the first capillary pressure step). de Waal et al.[2] injected oil into high porosity, high permeability samples at the rate of 1 PV/d and noted that a uniform saturation distribution (constant n) was only achieved when Sw fell below 40%. They concluded that the high injection rate and the difference in permeability between the samples and the semipermeable membrane were the causes of the nonlinearity of the I versus Sw relationship observed over most of the Sw range. Sprunt et al.[8] used X-ray CT scans to monitor saturation distribution along their core samples. They varied the capillary pressure and showed that there were difficulties in achieving homogeneous saturation for the two high porosity and high permeability grainstone samples desaturated at constant oil/brine capillary pressure. They concluded that a uniform relation of I versus Sw was not obtained because of the front created. Gray et al.[9] measured I for sandstone samples at a low constant injection rate (0.02 cc/hr), selected so that an insignificant pressure drop existed over the sample throughout the desaturation process. However, a linear I versus Sw log-log plot was not achieved except for Sw values less than 45%. Elashahab et al.[10] used a multiple potential electrode system for I measurement to enable assessment of the saturation distribution and end effects. Jing et al.[6] measured I for sandstone samples using a relatively high constant injection rate (0.25 cc/hr) and used X-ray CT scans to monitor the saturation distribution. A linear I versus Sw relation was obtained for these samples at Sw < 55%. Stalheium [14] argued that the saturation exponent should be a constant; however, Lyle and Mills [4] had previously shown theoretically that the laboratory-derived Archie[2] saturation exponent may differ from the actual reservoir value, and concluded that whenever the core saturation is nonuniform, the I versus Sw log-log plot will exhibit curvature.

Longeron et al[15] measured resistivity indices and capillary pressures using crude oil to investigate the effect of wettability on n, and showed that two values of n could be obtained. However, they used oil with a fixed viscosity throughout the experiments (μ_o = 8 MPa.s) and did not take into account the effect of the viscosity ratio between oil and brine. A comparison study of n at ambient and reservoir conditions was performed by Sondena et al[19] using crude oil. They concluded that the effect of wettability is more influential than that of pressure and temperature, but did not examine the effect of the brine/oil viscosity ratio. In their comparison study between continuous injection and porous plate techniques, Gray et al[9] concluded that there is fair agreement between the two techniques in resistivity determination, but they gave no consideration to others factors such as viscosity, density and interfacial tension. One important study of the effect of fluid characteristics on n was carried out by Grattoni et al[3]. They

concluded there is some evidence for the influence of factors such as viscosity ratio and capillary number on n.

The present work was under taken in order to follow up the work of Grattoni et al[3]. An experimental investigation was proposed in which repeated resistivity index measurements are carried out on the same core samples at different injection rates and viscosity ratios. Ten carbonate samples, 1.5" in diameter and 3" long, covering a wide range of porosity and permeability were selected for study; the sample properties are given in table (1). Resistivity index measurements by the continuous injection technique were carried out on these samples at various injection rates.

Table (1)

Sample No.	Porosity%	Permeability	Sample No.	Porosity	Permeability
1	27.3	25.1	6	18.5	3.1
2	13.5	8.5	7	15.2	1.9
3	30.2	23.2	8	16.3	1.2.
4	12.9	2.4	9	32.8	66
5	11.6	2.1	10	16.1	8

EXPERIMENTAL PROCEDURE

Experiments were carried out on the selected carbonate samples using two levels of injection rate (0.03 cc/hr and 0.15 cc/hr), and two levels of viscosity ratio (0.6 and 0.1). The samples, fully saturated with brine of concentration 100 g/l, were mounted in a multiple core holder made of aluminum and subjected to an initial confining pressure of 400 psi, which was subsequently increased to 3000 psi. The sample pore volume was calculated based on the brine volume collected in pipettes attached to the outlet of each sample. The system was allowed to come to equilibrium and oil was then injected at one end of the sample and brine was expelled at the other end through a semipermeable membrane, used to prevent passage of the oil at the outlet of the sample. The semipermeable membrane was supported on a brine saturated high porosity glass disc. Both voltage, phase angle and temperature were monitored continuously during the oil injection process. All samples had previously been made preferentially water-wet by first cleaning with methanol, then firing to 600^{o}C for one day in a high temperature furnace[11].

Before the desaturation process was begun, the resistivity of fully saturated samples (Ro) was measured. The oil/brine desaturation process was then started and I measured when both capillary equilibrium and electrical equilibrium were established at the confining stress used. This equilibrium was indicated when there was no further change in resistance (i. e. no further fluid redistribution along the core length). The average core saturation was calculated volumetrically by deducting the volume of brine displaced from the pore volume. Oil was injected at the rate of 0.03 cc/hr firstly for all samples, then at rate of 0.15 cc/hr, and the samples were recleaned after each step. A displacement pump equipped with a piston was connected to the core holder. The amount of displaced fluid was measured by a calibrated potentiometer connected to the pump piston and the pump was regularly re-calibrated for the experimental conditions. The samples were subjected to re-cleaning to remove oil contamination and to keep them in water-wet condition throughout the experiment. The resistance of the samples was measured at 1kHz, to minimise polarization effects[12]. The resistivity values were corrected for slight temperature variations using Arp's equation[13].

For the second part of this experimental investigation, the resistivity index measurements were carried out at low and high viscosity ratios. The other six samples (previously saturated with brine of μw =1.2 cp) were loaded to the core holder, then the oil/brine (μo =2 cp) desaturation process was started, and resistivity indices measured when capillary and electrical equilibrium were reached (indicated when there was no further change

in resistivity). The average core saturation was calculated volumetrically by deducting the volume of brine displaced from the pore volume. After resistivity index measurements were accomplished for these samples at high viscosity ratio, the samples were unloaded, subjected to recleaning, then reloaded for measurements at the low viscosity ratio (μw= 1.2 cp and μo =12 cp).

RESULTS AND DISCUSSION

After several resistivity readings were taken, Sw was determined. Figures 1, 2, 3, and 4 show the measured resistivity index values versus average brine saturations for the samples at the low and high injection rates. Figures from 5 to 10 show I vs. Sw for the samples at different viscosity ratios. By inspection of the plots of I versus Sw for these samples, it can be seen that a linear I versus Sw correlation holds on log-log plot over most of the range of Sw in cases of high injection rate and low viscosity ratio.

Effect of Injection rate:

When the nonwetting phase is injected into the sample to displace the wetting phase, the larger pores will be penetrated first because they present less resistance. As desaturation progresses, a saturation heterogeneity may develop due to the bypassing of smaller pores, and this will lead to nonlinearity of I versus Sw. This might be expected to occur with the carbonate samples tested here, which have bi-modal pore size distributions. However, the value of injection rate selected also has an important influence. The high injection rate in sample 1 (Fig. 1) appears to be optimal, since a linear I versus Sw relation was obtained (for Sw <80%). Also, for sample 2 (Fig. 2), a linear relationship was obtained over a wide range of Sw (Sw < 75% and < 65%) for both injection rates and the two cases show good uniformity of I/Sw correlation, despite a difference of 30% in n. In sample 3 (Fig. 3) both curves are nonlinear, but for the high injection rate, the curvature is less. In sample 4, although the low rate generates higher n values, both cases produced a fairly uniform I/Sw correlation (Sw < 75% and < 65%). The disadvantage of the low injection rates is that fingering may occur, leaving a thick film of water behind it; this may lead to a nonequlibrium saturation distribution, invalidating the I versus Sw relationship.

Effect of Viscosity Ratio:

In the second part of this experimental investigation, for all six samples, the low viscosity ratio produced a more uniform I/Sw relationship. For sample 5 (Fig. 5), the most uniform section of the curve is for Sw < 43%. In sample 6 (Fig.6) a uniform I/Sw relation was found in the case of low μ_R at Sw < 70%, and the difference in n was found to be 7%. In sample 7, although it has a unimodal pore system which usually produces a fairly uniform relation of I vs. Sw, two different curves were obtained due to the effect of viscosity ratio (Fig.7). In sample 8 (Fig.8) the two levels of viscosity ratio produced a uniform I/Sw relation (Sw < 75%), while in sample 9 (Fig. 9) the uniform correlation was obtained in the case of low viscosity ratio at Sw < 68%.

The viscosity ratio (μ_R) used in this paper is defined as the ratio of displaced (brine) fluid viscosity to the displacing fluid (oil) viscosity. High (μ_R = 0.6) and low (μ_R =0.1) ratios were used. The fluid flow through a porous medium (core or reservoir) results from various displacement events on the pore scale; these are affected by the interaction of the local pore structure with viscous, capillary and gravitational forces[3] . The displacement of water by oil in a porous medium is not a simple process and depends on many factors including the physical properties of the fluids. The flow mechanism during the displacement affects the fluid distribution and hence influences the resistivity index value. As the displacement process starts and continues, a front is formed. A transition zone exists after the first oil starts to displace brine and this zone travels along the core sample to the end. The shape of this zone depends on pore structure and the forces involved. Whenever this zone passes through the sample and

remains short while it progresses, it can be described as flat fronted, and small clusters of pores will be left unswept behind it. When the zone has greater length, it can be considered as a fingering front. This second type of front usually leaves larger clusters behind it than the first (flat fronted) type. These large clusters cause nonuniform saturation distribution, and a nonlinear I versus Sw relationship will be obtained [3] .

Viscous forces influence the shape of the front, and therefore different I versus Sw correlations are obtained for different viscosity ratios. Figs. 5 to 10 show I/Sw plots for all the tested samples at two viscosity ratios. At the lower ratio, the I versus Sw relation is more uniform than at higher ratio. Also the desaturation process at low μ_R covers a much greater Sw range than at high ratio. This can be attributed to the fact that a thin water film is left behind when the lower μ_R is used, while a thicker film of water is left behind at the higher ratio [3]. However, water was produced in the case of high μ_R even after oil had reached the sample end. It can be concluded that a uniform saturation distribution was obtained for the samples at low μ_R. The high viscosity ratio experiments produced n values lower than those for the low ratio, and the difference in n values reached about 13%. This significant difference confirms the need to perform resistivity index measurements using fluids have same characteristics as the reservoir fluid.

CONCLUSIONS

The influence of injection rate and viscosity ratio on the resistivity index versus brine saturation relation have important consequences for saturation exponent determination by the continuous injection technique. The results obtained above show that measurements of the resistivity index by the continuous injection technique using a single injection rate and a single viscosity ratio only may give an unrepresentative value of n, and lead to error in Sw determination.

In order to achieve precise and accurate evaluation of Sw from resistivity logs, one needs to have an in-depth understanding of the various factors affecting the laboratory determination of the saturation exponent. The fluids used in laboratory measurements should have characteristics close to the actual reservoir fluids. Sample preparation in the laboratory should be designed to represent the actual reservoir conditions as far as possible. In addition, the experiments should be performed at simulated reservoir conditions of pressure and temperature, so that the pore geometries can be restored as closely as possible to the original state.

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Fig.(1) I vs. Sw for sample 1 at different rates

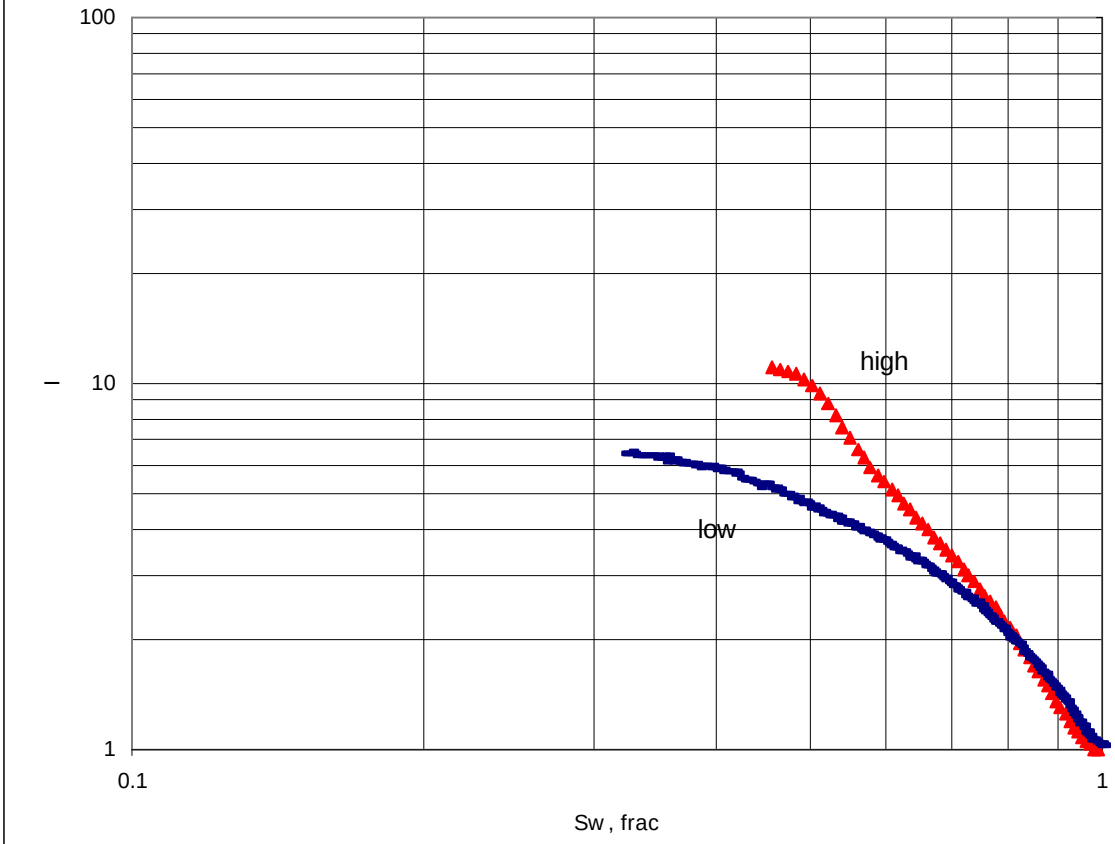


Fig.(2) I vs. Sw for sample 2 at differenr rates

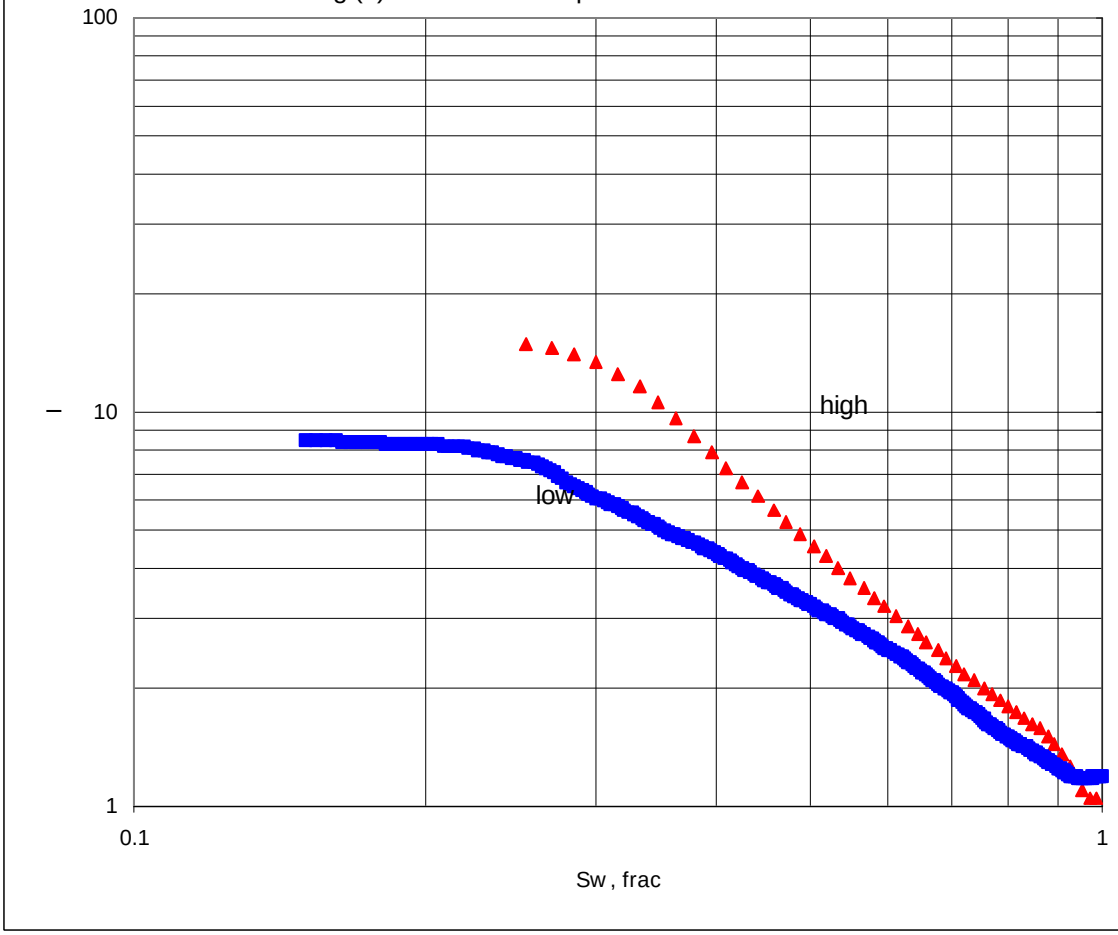


Fig.(3) I vs. Sw for sample 3 at different rates

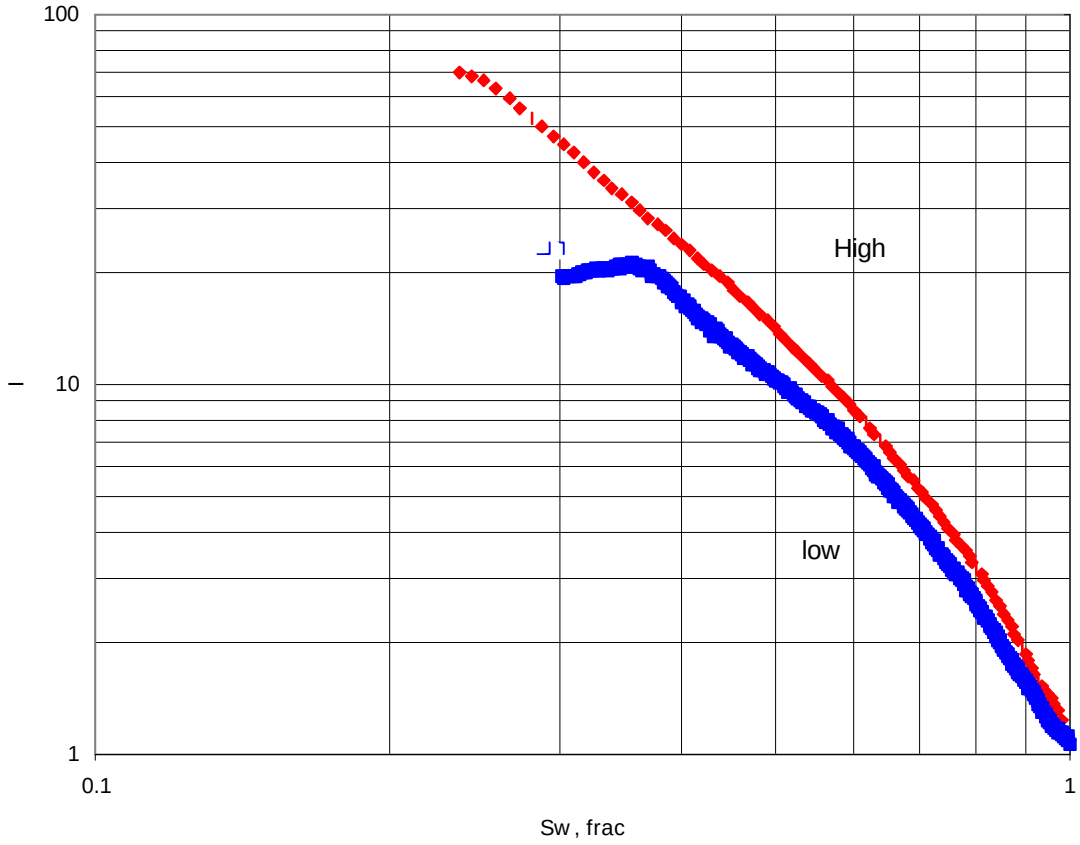
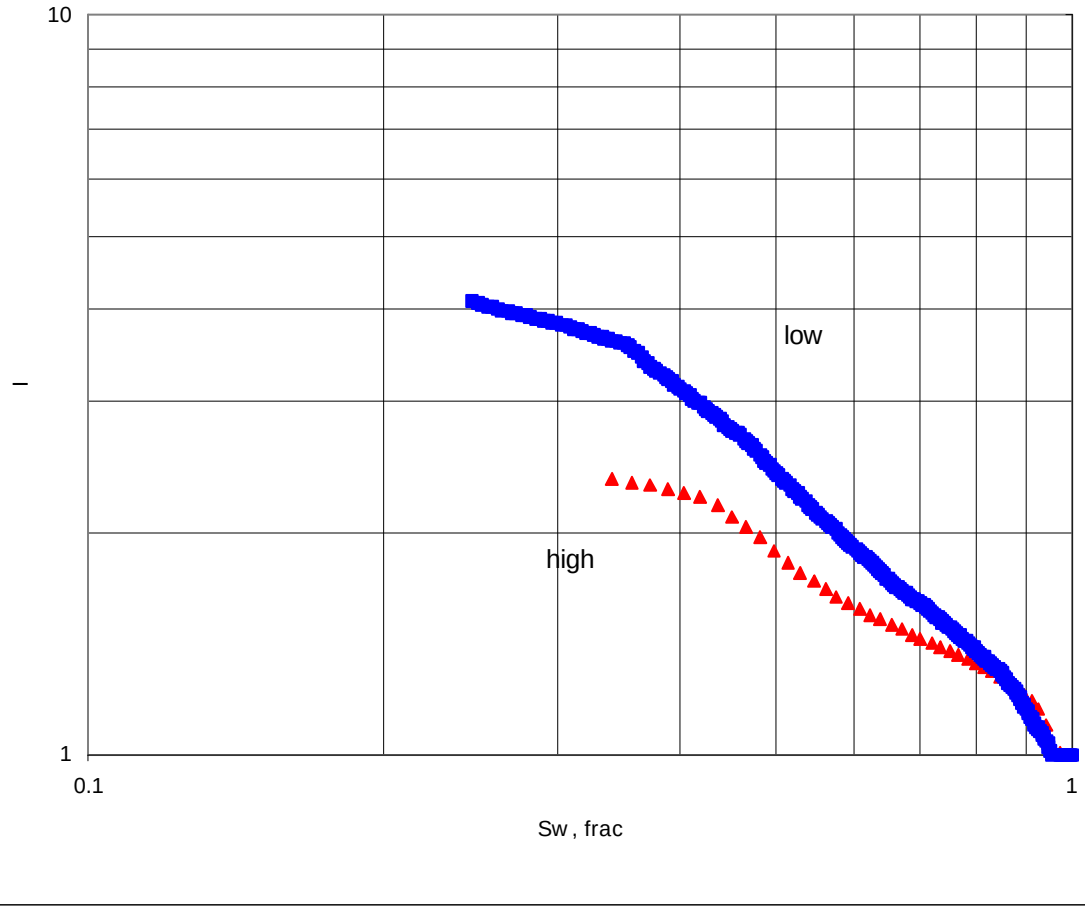
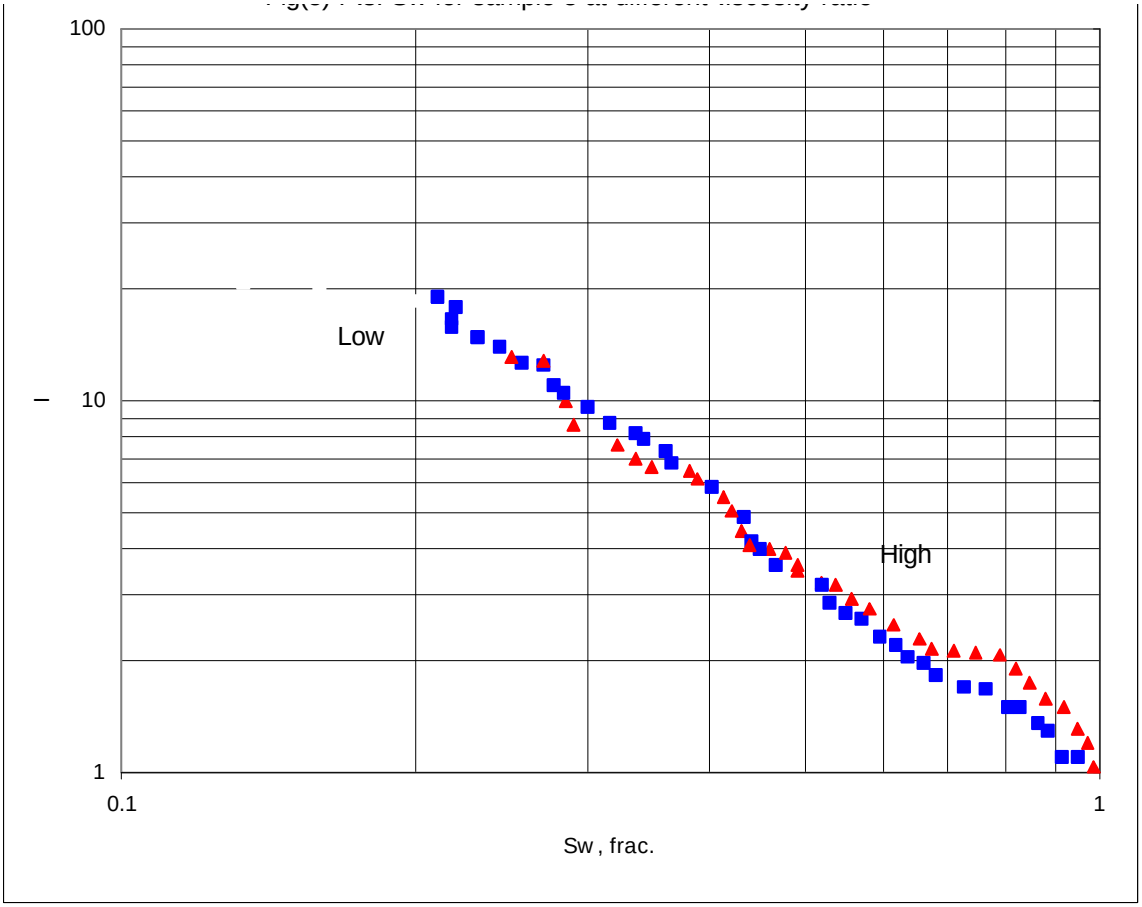
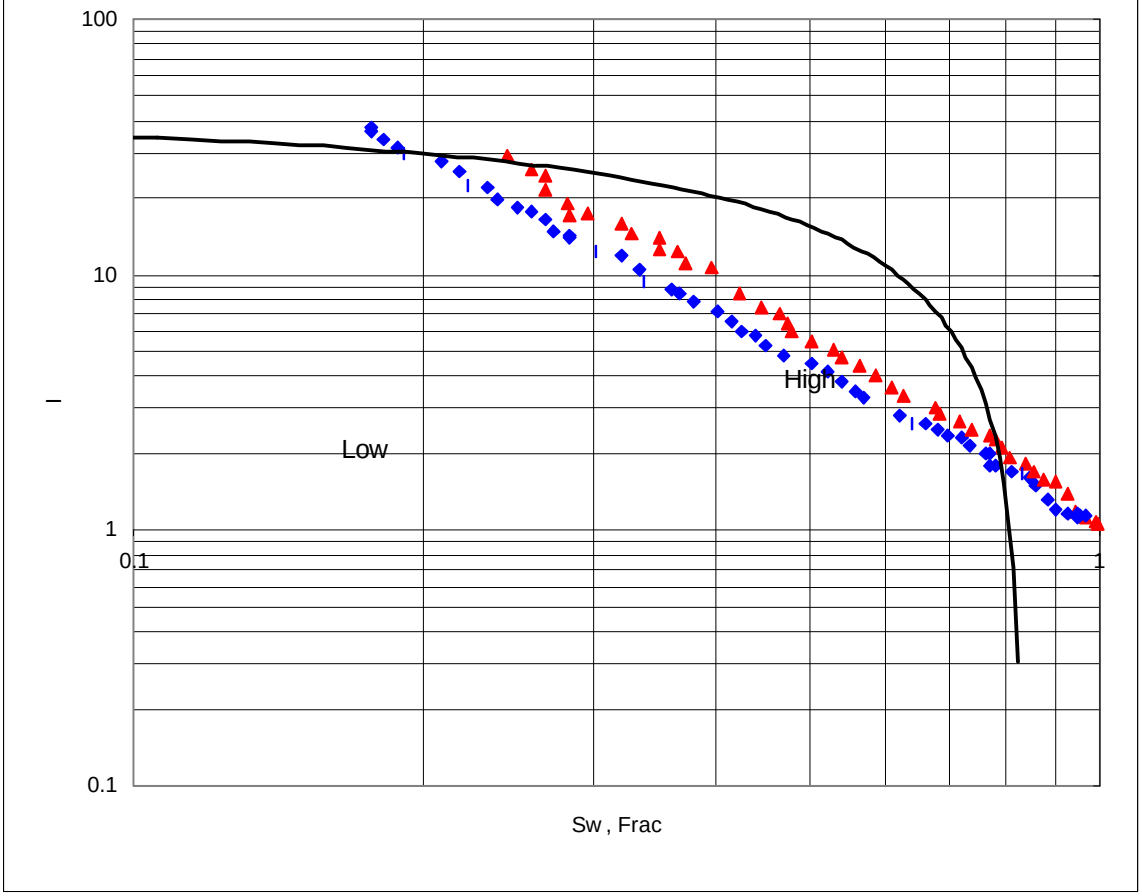


Fig.(4) I vs. Sw for sample 4 at different rates





Fig(6) I vs. Sw for sample 6 at different viscvosity ratio



Fig(7) I vs. Sw for sample 7 at different viscosity ratio

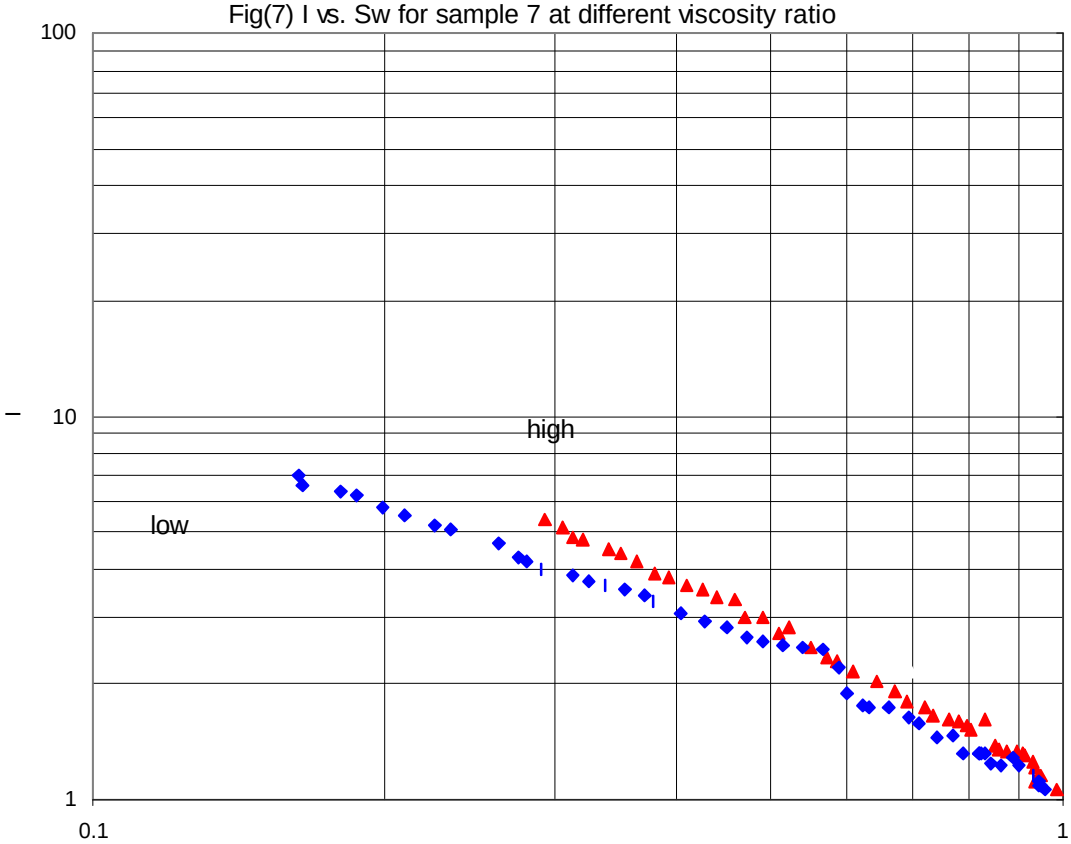


Fig.(8) Sw vs. I for sample 8 at different viscosity ratio