SCA-9838

MEASUREMENT OF CAPILLARY PRESSURE BY DIRECT VISUALIZATION OF A CENTRIFUGE EXPERIMENT

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ABSTRACT

A visualization method for obtaining capillary pressure relationships during centrifuge experiments was tested. It consists of recording and processing the video images of a rock sample at every spin rate. From these images, the local saturation at any location on the sample is obtained using a correlation that relates gray level to saturation. The capillary pressure is calculated using the measured average distance from the center of spin to the location of the local saturation measurement.

With the visualization method, gas-water capillary pressure curves for sand packs and for Berea rock were obtained that agree with those determined with the algorithm of Hassler and Brunner. The irreducible water saturations were observed to be quite low in experiments at high spin rates for Bond numbers greater than 0.00001.

Using video images, it was possible to explore the failure of the standard outlet boundary condition for centrifuge experiments, which maintains that the saturation of the displaced wetting phase during a drainage experiment is 100% at the outlet face of the sample. Results suggest that the standard outlet boundary condition fails for Bond numbers in excess of 0.0012.

INTRODUCTION

Capillary pressure is the difference in pressure between two phases in a porous medium. The difference in pressure is the consequence of curvature of the interface between the fluids and the interfacial tension. Capillary pressure can be correlated with fluid saturations in the rock. The resulting correlation is referred to as the capillary pressure relationship.

Techniques for capillary pressure measurement with reservoir fluids vary in accuracy. The centrifuge method is the most common method and is the main subject of this investigation. Hassler and Brunner, in 1945, were the first to analyze data from centrifuge experiments. Four assumptions are key to their work. First, capillary pressure at the outlet face of the core plug is zero. Second, the rock sample is homogeneous. Third, the effect of gravitational acceleration is small compared to the centrifugal field. And forth, the radial character of the centrifugal field is neglected.

The third and fourth of these assumptions have received attention in the technical literature of recent years (Ayappa *et al*., Christiansen, Forbes *et al*., Chen). Wunderlich reported some observations on the first assumption. Because there is sparingly little discussion of the first assumption in the literature, that was the focus of the research reported here.

For this research, methods for visualizing the saturation distribution in a rock sample during a centrifuge experiment were developed. With these video methods, the saturation at the outlet face of the rock sample was studied. Others (Chardaire-Riviere *et al*.) have used ultrasonic methods for monitoring fluid saturations in centrifuge experiments; however, the video methods are simple to use and have potential for collecting enormous quantities of data. The techniques, results, and conclusions are presented below.

EXPERIMENTAL TECHNIQUES

Centrifuge experiments for visualizing the interface between wetting and non-wetting phases for four sand packed samples and four slices of Berea sandstone are described in the sections below. In the first section, the centrifuge apparatus will be described. In the second section, the procedures for the centrifuge experiments will be described for the sand packs and the Berea sandstone. In the final section, the methods for interpreting experiments including method for visualizing saturations, and method for calculating capillary pressures will be described.

Apparatus

For this research, the commercial rotor for a Beckman J6-B centrifuge was replaced with a circular rotor on which were mounted two transparent sample holders. The circular rotor consisted of three pieces: an aluminum coupling that connects the rotor to the centrifuge shaft, an aluminum plate support, and a polycarbonate plastic plate (See Figure 1). The diameter of the plastic plate was 21 inches. The rotor was designed for a maximum spin rate of 2000 rpm. The radially symmetric rotor was chosen to minimize heating by viscous dissipation.

The sample holders were made of transparent polyacrylic plastic to provide for visualization of saturations in the porous samples and of the fluid drained from the samples during an experiment. Figure 2 shows a top view of the sample holder, and Figure 3 shows the placement of the sample holders on the plastic plate. With the sample holders, either sand packs or consolidated samples could be tested.

Procedures for Centrifuge Experiments

The following procedure was used for observations of displacements in Berea samples. (The procedure for sand packs was similar.)

1. Dry and weigh rectangular slices (2” x 3” x 0.2”) of Berea. Then record video images of the dry samples. These are termed the “0%” images.

2. Saturate the Berea samples with dyed water. Weigh the saturated samples, and record their video images. These images are termed the “100%” images.
3. Mount the sample holders containing the samples on the rotor in the centrifuge, and spin the samples at a selected speed. Record the speed.
4. Stop the centrifuge. Measure the amount of liquid drained from the porous samples, record video images of the samples at their new saturation conditions.
5. Repeat Steps 3 and 4 at increasing spin rates.

Stopping the centrifuge as specified in Step 4 is undesirable, but it was difficult to get a good video image while the rotor was spinning. Currently, we are working toward getting images while spinning. Table 1 shows the properties of sand-packs and Berea samples.

A black-and-white video camera was used to take pictures of the samples at every spin rate. This camera was connected through a VCR to a computer, which transferred the pictures into digital images. From these images, local saturations were determined by converting the gray level to saturation with a correlation that will be discussed later.

Measuring Saturations and Calculating Capillary Pressure

Capillary pressure Pc can be calculated using Eq. (1) if the fluid-fluid density difference $\Delta\rho$, the spin rate ω, and the radius r from the center of spin are known.

$$\Delta P = P_c(r) = \frac{1}{2}\Delta\rho\omega^2\left(r_o^2 - r^2\right) \quad (1)$$

In Eq. 1, r_o is the radius from the edge of the sample furthest from the center of spin. The radius r can be determined from the image of the sample. As shown in Figure 4, a rectangular area on the image of each sample is selected, then the distance from the top of the image to the center of the rectangular area and the average gray level for that rectangular area can be measured. The radius r equals the average distance from the top of the image plus the radius from the center of spin to the center of the top of the image. From the average radius, the capillary pressure can be calculated using Eq. (1). The rectangular areas were narrow in the radial direction, and long perpendicular to the radius.

RESULTS AND DISCUSSION

The results obtained from the centrifuge visualization experiments will be described in the sections below. The first section will discuss the centrifuge correlation between liquid saturation and gray level. In the second section, the results of the centrifuge experiments will be considered. In the final section, observations on the failure of the outlet boundary condition will be discussed.

Saturation Correlations with Gray Level

During this research, three methods were tested for developing correlations between observed gray level in an image and fluid saturation. These procedures are descussed elsewhere (Al-Omair). Here, just the method and correlation will be discussed.

In the centrifuge method, the average gray levels of the images collected at each step in a centrifuge experiment are corrected directly with the average saturation in the sample. The important advantage of this method is that it uses the results of a centrifuge experiment to develop the correlation. So, separate effort to develop a correlation is not needed. It would be instructive in the future to compare gray levels correlations from porous plate capillary pressure experiments with the centrifuge correlation.

The centrifuge correlation is compared with the "volume correlation" in Figure 5 for Sandpack Sample 4. (The volume correlation is obtained by injecting increasing amounts of dyed water into the sample, then measuring the gray level for each step.) We believe that the similarity between the two correlations lends validity to us of the centrifuge correlation. The centrifuge correlation for Berea Sample 5 with a best-fit line is shown in Figure 6.

Adsorption of the dye on the solid surface could greatly complicate interpretation of the results. While it is likely that some of the dye is adsorbed, the depletion of gray level from its maximum when the media is fully saturated toward the minimum of completely dry media indicates that adsorption was not an issue in these experiments. For applications with oils that are naturally colored, adsorption is probably a minor concern.

Capillary Pressure Relationship Analysis

The capillary pressure relationship for each sample was developed using the visualization method. For example, the video images shown in Figure 7 were analyzed using the centrifuge correlation for estimating the local saturations and Eq. 1 for calculating the capillary pressures. These relationships are compared in Figures 8 and 9 with those obtained with Hassler-Brunner:

$$S(P_{ci}) \;=\; \bar{S}(P_{ci}) + P_{ci}\,\frac{d\bar{S}(P_{ci})}{dP_{ci}} \qquad (2)$$

In Equation 2, S_W is the local saturation. The overbar denotes average saturation. P_{ci} is the capillary pressure at the inside edge of the sample. The visualization results are somewhat scattered, but they generally match the Hassler-Brunner results, which also show some scatter. It is believed that the scatter can be reduced by improved data collection techniques. Nonetheless, the experiments to date demonstrate the application of the visualization method.

Failure of the Outlet Boundary Condition

The images in Figure 7 show the movement with increasing spin rate of the threshold pressure interface. Here, "threshold pressure interface" refers to the boundary between sand 100% saturated with water and sand with lower water saturations. At this boundary, capillary pressure should equal the threshold pressure. As centrifuge speed increased, this interface moved toward the outer edge of the sample. At the highest speeds with sandpack samples, the interface could not be seen.

If the threshold pressure interface is detectable, then the standard outlet boundary condition (capillary pressure equals zero at the outlet edge) may be appropriate. But at higher spin rates, where the region is not detectable, the standard outlet boundary condition is likely not appropriate.

King et al. (1986) found that oil saturation can be driven below residual saturation in centrifuge experiments when the Bond number exceeds a critical value (0.00001). The Bond number N_B is defined

$$N_B = \frac{\Delta\rho\ k\ r\ \omega^2}{\sigma} \qquad (3)$$

In Equation 3, $\Delta\rho$ is the fluid-fluid density difference, k is the permeability, r is the radius, w is the angular velocity, and σ is the interfacial tension. The Bond numbers for different spin rates with the sand packs and the Berea samples are shown in Table 2. For the sand packs, the Bond numbers are larger than the critical value of King *et al*. The capillary pressure curve in Figure 9 for Sandpack Sample 4 shows very low saturations at highest spin rates. This result is consistent with the conclusion of King *et al*. For Berea, the Bond numbers at spin rates greater than 400 rpm exceed their critical value.

The Bond number may also be a suitable dimensionless quantity for gauging the failure of the outlet boundary condition. The standard boundary condition may have failed in sand pack experiments for Bond numbers greater than 0.0012.

Images of the Berea sample in Figure 7 show a region of high fluid saturation at spin rates up to 1000 rpm. Above that rate, it is difficult to see the high saturation region. The Bond numbers for the Berea experiments are much less than the Bond numbers for the sand pack experiments. So, one would expect to see a high saturation region at the outlet in all of the Berea experiments if the Bond number is the proper group for assessing failure of the standard outlet boundary condition.

CONCLUSIONS

1. Capillary pressure relationships obtained from visualization agree qualitatively with those obtained with the algorithm of Hassler and Brunner.

2. In experiments with high bond numbers greater than 0.00001, saturations were typically less than 5%. This result agrees with the observations of King *et al*.
3. At Bond numbers greater than 0.0012, the standard outlet boundary condition may have failed in experiments with sand packs. Failure of the standard outlet boundary condition was not clearly observed for experiments with Berea samples.
4. The local saturation can be estimated reliably from the centrifuge correlation.
5. This work demonstrates that significant centrifuge experimentation is possible with very simple and inexpensive apparatus.

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Table 1. Properties of Porous Media

Sample	Porosity %	Permeability Darcies
1: Sand Pack	36.2	12.8
2: Sand Pack	34.1	12.8
3: Sand Pack	7.9	12.8
4: Sand Pack	35.1	12.8
5: Berea	24.9	1.51
6: Berea	27	1.51
7: Berea	24.2	1.5
8: Berea	23.3	1.5

Table 2. Bond Numbers

Spin Rate rpm	Sand Back	Berea
50	1.20E-05	-
100	4.60E-05	-
200	1.90E-04	-
300	4.20E-04	4.90E-06
400	7.40E-04	8.70E-06
500	1.20E-03	1.40E-05
600	1.70E-03	2.00E-05
1000	-	5.50E-05
1100	-	6.60E-05

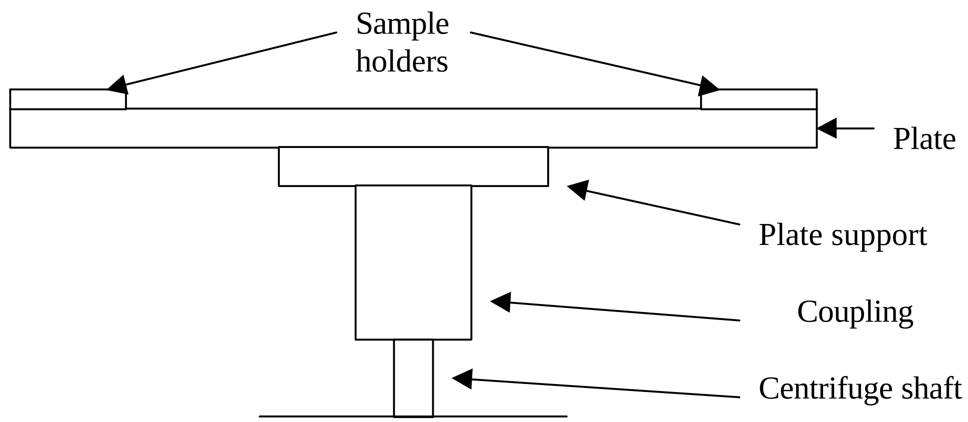

Figure 1 : Schematic Diagram of the Apparatus

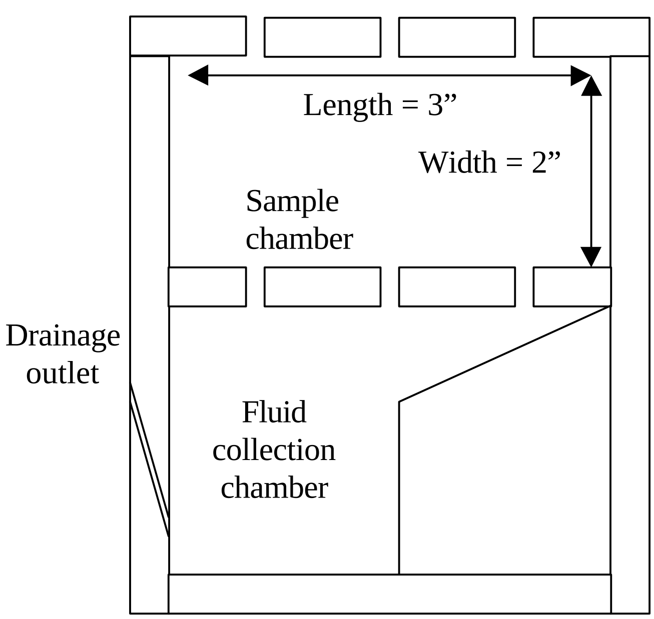

Figure 2 : Top View of the Sample Holder

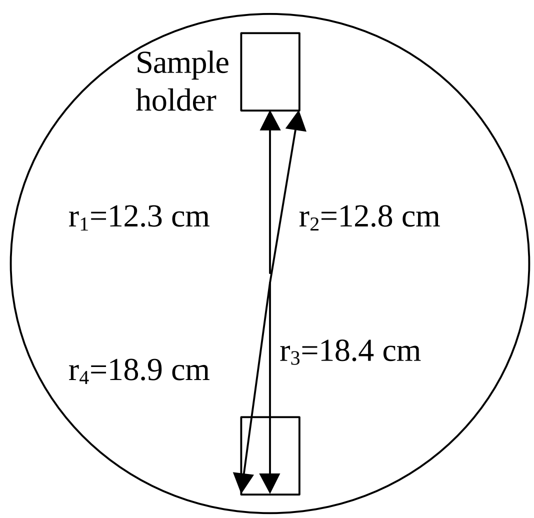

Figure 3 : Placement of Sample Holder Rotor Plate

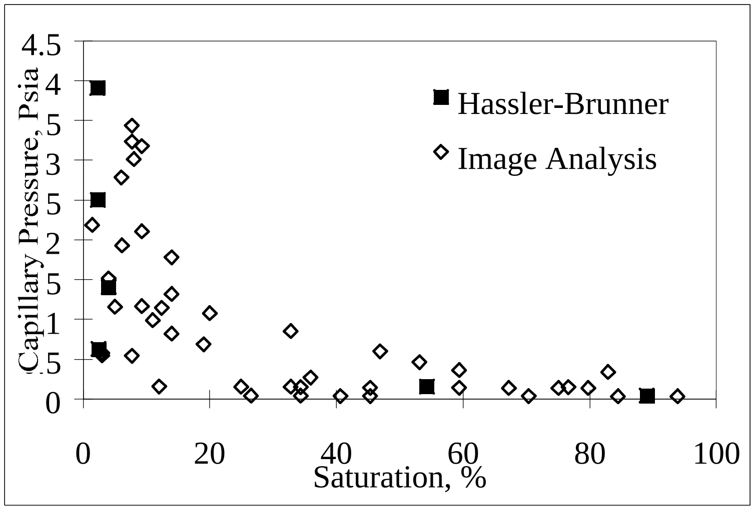

Figure 8 : Measured Capillary Pressure Relationship, Sample 4

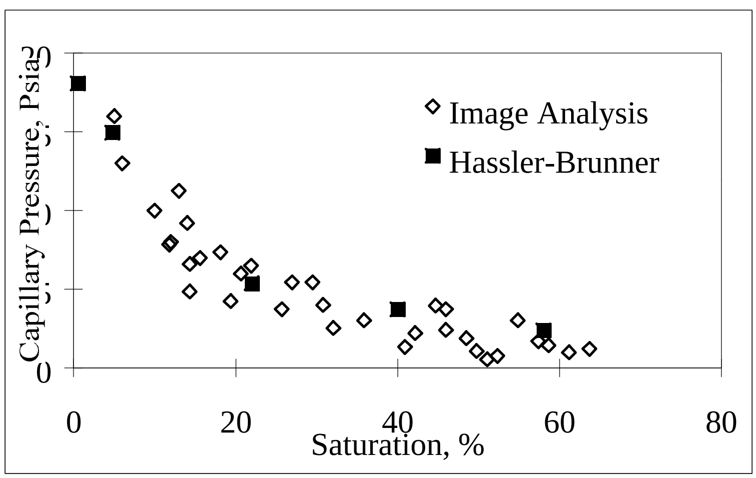

Figure 9 : Measured Capillary Pressure Relationship, Sample 5

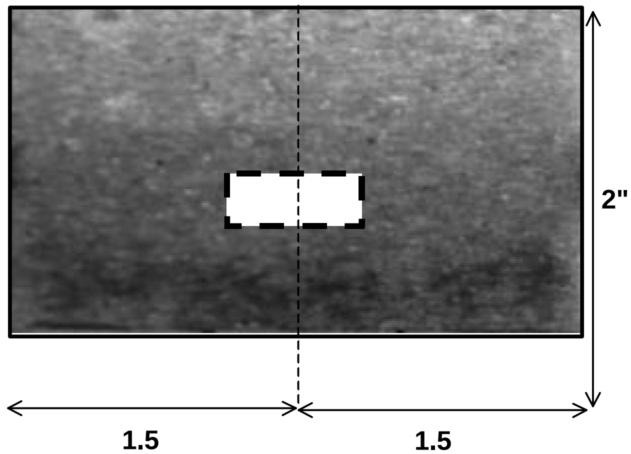

Figure 4 : Selection of a Rectangular Area from an Image

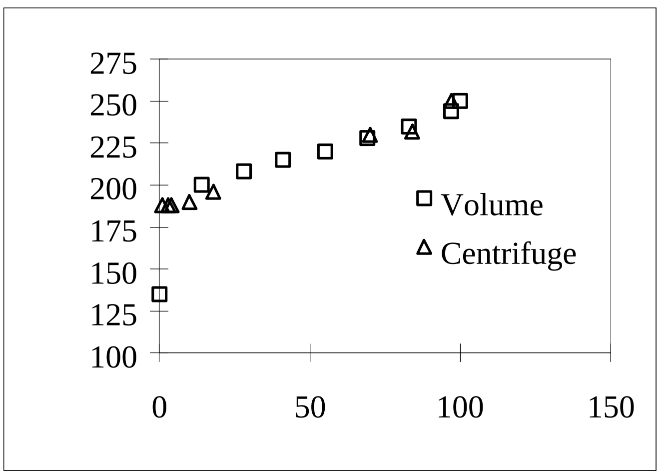

Figure 5 : Comparison Among the Two Correlations for Sample 4

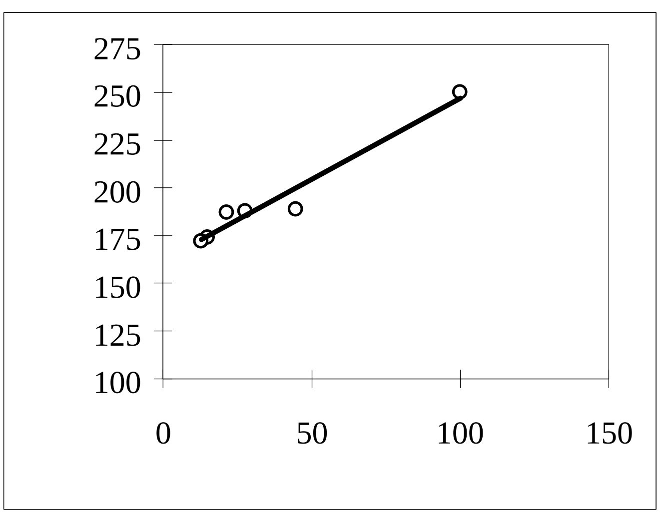

Figure 6 : Centrifuge Correlation for Sample 5

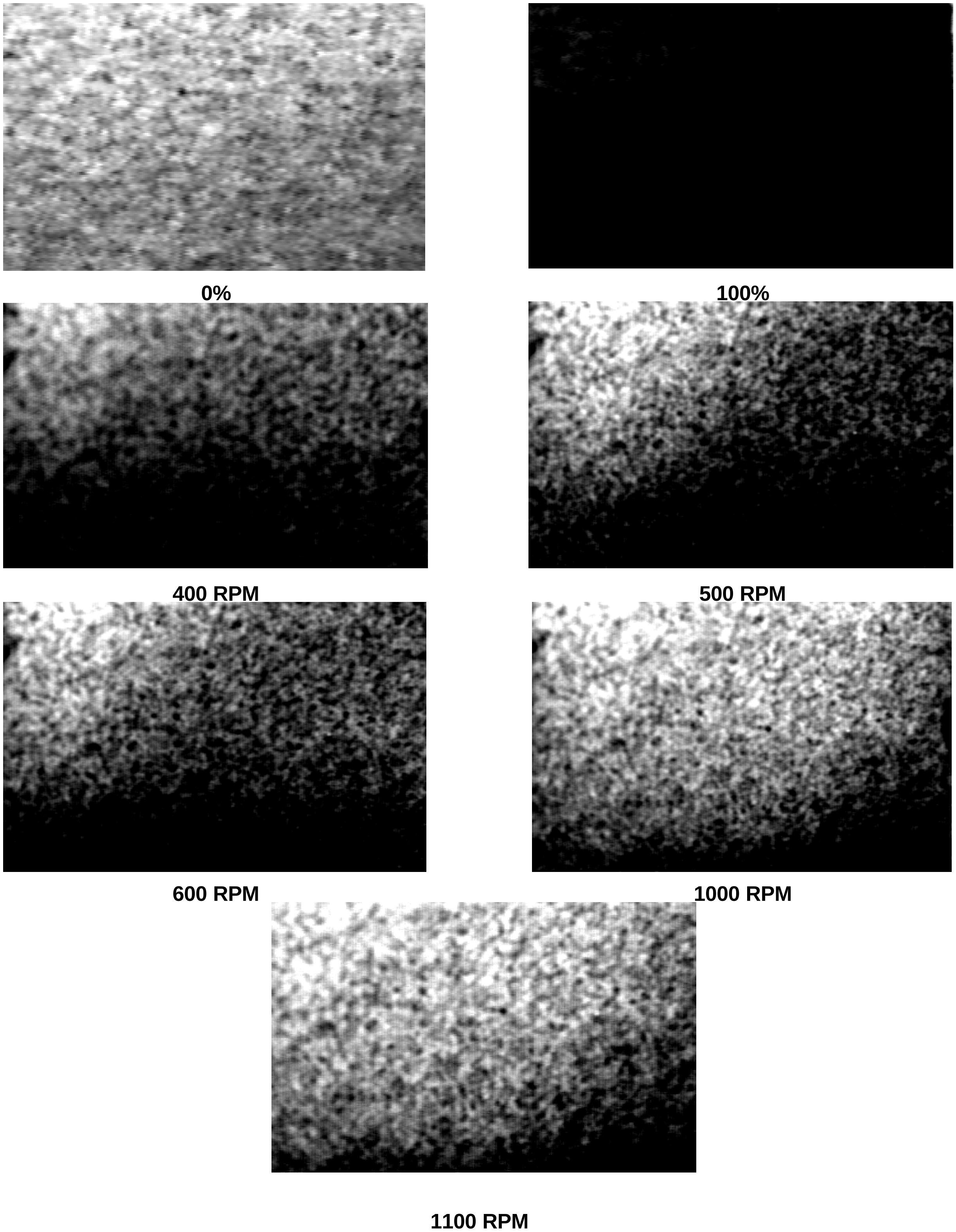

Figure 7 : Vidio Images for Berea Sample 5. The top images serve as visual calibration for saturation in the lower images