An Experimental Method to Measure the Porosity from Cuttings:
Evaluation and Error Analysis

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ABSTRACT

As an economical approach to formation evaluation, drill cutting analysis provides significant information on petrophysical parameters which help us to understand the reservoir behavior. Researchers are gradually paying more attention to the study of drill cutting samples which potentially promote and enrich the reservoir characterization process.

This thesis project concentrates on measuring the porosity from cuttings. An evaluation of the improved method is presented by comparing porosity data estimated from artificial cuttings with various sizes to the reference value measured from core samples. Since the estimation of bulk volume is not practically possible for cutting samples, the measurement of porosity from cuttings depends on the grain volume V_g and the pore volume V_p . According to the procedure presented by IFP, the volume of grain is calculated from the weight of dried cuttings applying an average grain density. As an improved point, we will use more accurate values of grain density which are obtained from conventional core analysis for measuring cuttings porosity. Additionally, the pore volume is calculated by using a saturation method adapted to cuttings.

The cuttings are obtained from crushed cores with different permeabilities and screened into four different sizes. The analysis of results shows that estimating the porosity from cuttings by using the proposed method is effective and reasonable. There is a close relationship between the results and the size of cuttings. After removing excess liquid between cuttings, the measured porosity from all cutting sizes is overestimated. Cuttings with the smallest size A (0.425-0.85 mm) show the greatest deviation. For cuttings with larger size, the measured porosity ranges smaller over time compared with that from cuttings of smaller size. We use one hour as the optimum desaturation time which corresponds to the measured results. The largest size D (2.8-4.0 mm) gave the best results that generated the minimum error. We also discussed the influence of permeability on the results.

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NOMENCLATURE

Roman

D	<i>Diameter, cm</i>
L	<i>Length, cm</i>
k	<i>Permeability, mD</i>
V	<i>Volume, cm³</i>
W	<i>Weight, g</i>

Greek

ϕ	<i>Porosity (fraction)</i>
ρ	<i>Density</i>

Subscripts

e	<i>Effect</i>
b	<i>Bulk</i>
ma	<i>Matrix</i>
g	<i>Grain</i>
p	<i>Pore</i>
s	<i>Saturated</i>
d	<i>Dry</i>
$fluid$	<i>Fluid</i>
r	<i>Reference</i>
i	<i>Initial</i>
f	<i>Final</i>
$t0$	<i>The beginning of desaturation process</i>

CHAPTER I

INTRODUCTION

Increasingly technological improvement of subsurface tools combined with powerful computers is making a great contribution to reservoir characterization. Excellent numerical models established on the basis of parameters and attributes from formation measurements not only provide a detailed reservoir description but also make accurate simulations of the behavior of oil and gas reservoirs, even in complicated cases. In order to keep these models running precisely and effectively, a large amount of reservoir data is required. Therefore, lots of tools have been invented in the energy industry and presented to the market. They have the functions of measuring various reservoir parameters, such as pressure, temperature, density, and resistivity, etc. Providing the necessary formation information, these tools help reservoir engineers to have a better idea of reservoir behavior and to establish reasonable development plans, as well as to predict oilfield production performance. Therefore, researchers are trying to apply all available means to extract petrophysical parameters, including the study of drill cuttings.

Even though a large volume of data can be gathered from real-time monitoring of reservoir parameters during exploration and development of an oilfield, there is still a need for a more detailed understanding of underground characteristics. For this reason, reservoir data achieved directly from core sample analysis becomes a valuable source of information, while this is only feasible for situations in which coring can be conducted during drilling projects. It should be admitted that in some special reservoirs, coring is impractical if not impossible. For example, coring is not practical when reservoirs have been developed in the form of horizontal wells. Generally, it is more practical to operate coring for conventional wells than for non-conventional wells. Also, for economic reasons or because of difficult drilling conditions, it is impossible to core these kinds of reservoirs. As the main source of data for reservoir description, cores play a major role in the field of formation evaluation. For reservoirs

for which coring is unavailable, drill cuttings produced during drilling operations may substitute for core samples and help us describe the reservoir and understand its behavior.

1.1 Recognition of Drill Cuttings

Drill cuttings, also called rock fragments, usually present in millimeter size and are produced from subsurface formation as the rock is broken by the drill bit head, constructing a borehole. The cuttings are brought to the surface by the circulation of drilling fluid during drill operations and separated by shale shakers or by cyclone separators.

For a long time, drill cuttings were considered waste material that needed to be disposed after environmental treatment. With the rapid development of the oil and gas industry, researchers gradually have paid more attention to the study of drill cutting samples that promote and enrich the reservoir characterization process. Initially, the use of drill cutting samples was limited to the estimation of lithologies and visual porosity ranges at the well site for gross stratigraphic correlation and operational purposes (Solano et al. 2012). The purpose of this evaluation is to ensure the drilling project proceeds smoothly.

1.2 Drill Cuttings Analysis in Mud Logging

As an economic approach to formation evaluation, drill cutting analysis has become an important part of mud logging. Mud logging, more elegantly and more informatively referred to as hydrocarbon well logging, includes measurements of both the progress of the drilling process and the contents and properties of the formations drilled, such as rock type and fluid content. Some of the information is vitally important to the formation evaluator and reservoir engineer. There are two advantages of mud logging: the availability on a semicontinuous basis of an actual formation cutting analysis that provides immediate indications of rock type and hydrocarbon presence; the ability to predict drilling problems before they become unmanageable (Bateman 2012).

Through some measurement techniques and conventional analysis of drill cutting samples collected from field, we may have a basic knowledge of rock fragments. For instance, by visual or microscope inspection, much information can be obtained, including approximate porosity, lithology, texture, and hydrocarbon content, etc. In addition, if hydrocarbons are still retained in the cutting samples after being circulated up to the surface, they can be detected by smelling, visual inspection under ultraviolet light, and by being subjected the sample to chemical reagents.

1.3 Research Status in Drill Cuttings

In recent decades, many papers have presented new technology and methods to evaluate more accurately and comprehensively the reservoir that use drill cuttings.

Researchers can determine Nuclear Magnetic Resonance (NMR) petrophysical parameters from drill cuttings (Mirotchnik et al. 2004). Using their procedures on drill cuttings during mud logging allows us to measure porosity, absolute permeability, and irreducible water saturation.

A novel approach for drill cutting analysis can also help drilling fluids design (Guzman 1999). After good collecting and preparation of drill cuttings, the enhanced analysis provides relevant information about reservoir mineralogy and pore geometry. If these are studied properly by using a combined technique of Scanning Electron Microscopy (SEM), it is possible to get key parameters to help in the design of fluids to prevent invasion during drilling and completion operations and in the choice of screens for control of solids in surface equipment.

In the future, drill cutting analysis may become a significant approach to formation evaluation work in unconventional reservoirs. Horizontal drilling technology has been widely used when developing tight formations. However, in most horizontal wells, the data for detailed analysis is insufficient. To deal with this problem, a new method has been put forward for complete petrophysical evaluation based on information that was obtained from drill cuttings in the absence of well logs (Ortega and Aguilera 2012). As a powerful petrophysical tool, this method allows

quantitative estimation of water saturation, capillary pressure, pore throat, flow units, porosity exponent m , and true formation resistivity. It proves that drill cuttings are a good source of information that provides practical and complete evaluation of tight reservoirs where well logs are limited.

The merits of using drill cuttings for analysis are obvious since they are the first physical representatives that come directly from the reservoir. With the unceasing progress of technology, it is expected that the trend of focusing more research on drill cuttings and extracting valuable information from them will accelerate.

1.4 Objective of the Project

The aim of this project is to determine porosity from drill cuttings. Though there are already relevant methods to solve this problem, the accuracy of methodology needs to be evaluated. It is valuable to analyze and discuss the factors that affect the measurement accuracy. In this project, a conventional way is applied to measure porosity of drill cuttings. The three groups of cuttings are crushed from core plugs with three different permeabilities. Then each group of artificial cuttings will be screened into four different size intervals.

Prior to work on the cuttings, porosity of cores should be measured and used for calibration purpose. After a series of group experiments, the porosity can be obtained in different cases of cuttings. The comparison between porosity from cores and cuttings may reveal some relationships between the size and permeability of cuttings and porosity as well as how those factors influence the accuracy of the employed method.

In order to achieve the goal, this thesis project has been divided into six chapters. In the first chapter, we present an introduction to the topic that includes the basic knowledge of drill cuttings and related research background. The following chapter is literature review which summarizes the theory and methodology that contribute to the estimation of formation porosity and permeability from drill cuttings. In Chapter III, the designed measurement method and experimental work will be

reported in detail. The next chapter is to analyze and evaluate the results obtained from our previous laboratory work. Finally, the conclusions and recommendations for further study are stated in Chapter V and VI.

CHAPTER II

LITERATURE REVIEW

In retrospect, the study on drill cuttings has been conducted for more than half a century. A large number of papers in literature proposed various technologies or approaches to extract information from drill cuttings which represented formation properties. To begin with, we discuss the research value and meaning of cuttings at present followed by a briefly review of the knowledge of porosity and the conventional measurements. Then methods emphasizing determination of porosity from cuttings will be listed and evaluated. In addition, as another important petrophysical parameter for reservoir characterization, permeability measurement approaches on cuttings are also reviewed.

2.1 Research Significance on Drill Cuttings

When we talk about cuttings, cores should be also mentioned. They are two types of rock samples through which the representative reservoir attributes could be found. The collection of core samples is critical to having a comprehensive understanding of the reservoir. The data from rock samples can be widely used for various purposes, such as log calibration, performance prediction, reservoir simulation, development plan designing. Conventional cores are cut by lowering a special core bit and a long core barrel into the well which are retrieved and bring rock samples back to the surface. On average, since about 60 to 90 samples (typical core size is 1 in. in diameter and 1 3/4 in. long) are retrieved at one time, couples of trips are required to collect enough samples from the target zone of a well. Such requirements give rise to a series of drawback of coring: lower drilling rate than usual, high costs caused by changing core bit with extra trips, operational difficulties and application limitations. In the cases of horizontal or maximum reservoir contact wells, it is difficult to perform coring projects.

Drill cuttings play very important roles in formation evaluation (Santarelli et al.

1998). Agip SPA investigated the possible use of cuttings to determine the properties of formations encountered during drilling operation. They undertook a research project which was aimed at describing in real time the formations on the basis of measurements on cuttings. The project proved that it was possible to perform measurements of a bulk of parameters, such as P- and S-wave velocities, rock strength, deformability, porosity, permeability, residual fluid content, saturation and electrical resistivity. On one hand, the paper discussed some drawbacks of other traditional technologies in formation evaluation, including cores measurement, measurement while drilling (MWD), and logging while drilling (LWD). On the other hand, the advantages and disadvantages of formation evaluation by means of estimation from cuttings were also analyzed. The obvious merit mentioned in the paper was that all the measurements were extremely economical and time-saving compared to traditional formation evaluation techniques, whether coring or MWD and LWD techniques. However, utilization of drill cuttings had its limitations. Once encountered very weak formations, the cuttings were not always available at the shale shakes, so the collections process became difficult. Also, the techniques presented in the paper could not correctly evaluate coarse-grained formations or formations with large pores.

This thesis project concentrates on measuring the porosity from cuttings. Porosity is a measure of the void spaces in a formation. It can be used for determining permeability of a formation and may be helpful in interpreting well logs. Lots of useful applications illustrate the significance of exploring a way for estimating the porosity of the reservoir drilled by a well by some means other than coring. As stated previous, coring all formations is neither economical nor practical even for explorations wells. In addition, during the drilling project, situations keep changing and plan needs to be adjusted according to actual circumstances. For example, coring program has been conducted for the target section as designed drilling plan. After certain layers are drilled, the geologist need more complete information for evaluation. The value of porosity would be of great assistance and the drill cuttings, continuous circulated up to the surface with drilling mud, can also support further analysis.

For soft formations, it is feasible to measure porosity after drilling with cores retrieved by side-wall coring devices. But in hard consolidated formations, the conventional coring procedure is not practicable in some cases and it is necessary to look for other paths for determining porosities. At this time, the examination of drill cutting becomes the first choice (Westbrook and Redmond 1946).

2.2 Porosity

2.2.1 Definitions

From the viewpoint of petroleum engineers, the two most important petrophysical parameters for reservoir characterization are porosity and permeability. The porosity of a rock is a measure of the storage capacity (pore volume) that is capable of holding fluids (Ahmed 2002). Porosity is defined as the ratio of the pore or void volume to macroscopic or bulk volume. It is a static property that can be measured without flow. Sometimes porosity is reported as a percentage, and it should always be expressed as a fraction for calculation. In equation form:

$$\phi = \frac{V_p}{V_b} \quad (2.1)$$

$$\phi = \frac{V_b - V_{ma}}{V_b} \quad (2.2)$$

$$\phi = \frac{V_p}{V_p + V_{ma}} \quad (2.3)$$

Where ϕ is porosity, V_p is pore volume, V_b is bulk volume, V_{ma} is volume of matrix minerals (solid volume or grain volume).

With the deposition of sediments and the formation of rocks during past geological times, some void spaces that formed became isolated from the other void spaces by compaction process. Thus, the pore space can be divided into an interconnected space that allows fluid to flow and a disconnected space that is

unavailable to fluid flow. Two distinct types of porosity can be measured: total or absolute porosity and effective porosity. Total porosity is the ratio of all the pore spaces in a rock to that of the bulk volume. Effective porosity is the percentage of interconnected void space with respect to the bulk volume. For granular materials such as sandstone, the effective porosity may be close to the total porosity. While for shales and for highly cemented rocks such as some limestones, a large difference would be presented between effective and total porosity.

According to the mode of origin, porosity may be classified as either primary or secondary. Primary or original porosity is formed during the process of sediment deposition. Secondary porosity is developed by some geologic process subsequent to formation of the deposit. There are many factors that cause these changes in the original pore spaces, such as ground stresses, water movement as well as other types of geological activities after the original sediments were deposited.

Since only the effective porosity contains the recoverable hydrocarbon fluids that can be produced from wells, it plays a crucial role in the prediction of origin oil in place. With such commercial value, particular attention should be paid to the means of measuring the effective porosity.

2.2.2 Measurements

According to the definition of porosity, it is obvious that the porosity can be determined by measuring any two of the three quantities: bulk volume, pore volume or grain volume. The porosity of a reservoir rock may be determined by following approaches:

- Core analysis
- Well logging technique
- Well testing

It is difficult to evaluate which source of porosity is more reliable without reference to a specific interpretation problem. All the techniques will generate correct

porosity data under favorable conditions. The core analysis method has the merit that it is unnecessary to make assumptions as to mineral composition, borehole effects, etc. Nevertheless, since the volume of the core is less than the rock volume which is analyzed by a logging device, porosity values obtained from logs are generally more accurate in heterogeneous reservoir. The following section will discuss the estimation of pore volume, grain volume and bulk volumes from core plugs.

2.2.2.1 Bulk Volume Measurement

Even though the bulk volume may be calculated from measurements of the dimensions of a uniformly shaped sample, the usual procedure applied is the observation of the volume of fluid displaced by the sample. The displaced fluid can be observed either volumetrically or gravimetrically. For any procedure, the key point is to prevent fluid from flowing into the pore space to the rock. This can be achieved (1) by coating the sample with paraffin or a similar substance; (2) by saturating the core with the fluid into which it is to be penetrated; (3) by employing mercury.

Gravimetric determinations of bulk volume can be achieved by measuring the loss in weight of sample when immersed in a fluid or by measuring the change in weight of a pycnometer with and without the core sample.

2.2.2.2 Pore Volume Measurement

All the ways of measuring pore volume generate effective porosity. They are based on either extraction of a fluid from the rock samples or the penetration of a fluid into the pore spaces of the rock.

One of the most used methods is the helium technique by applying Boyle's law. Since this technique would be applied in this project, the helium porosimeter apparatus and measurement procedures will be described in detail in the next chapter.

The main reasons that utilize helium instead of other gas are as follows:

- a) Its small molecules can penetrate small pores rapidly.
- b) It is inert and does not adsorb on rock surfaces.

- c) It can be considered as an ideal gas for pressures and temperatures usually used in the test.
- d) With a high diffusivity, using helium allows us to determine porosity of low permeability rocks.

Another method of pore volume measurement is to saturate the sample with a liquid of known density. Then use the weight difference before and after saturation to calculate pore volume.

2.2.2.3 Grain Volume Measurement

Grain volume is sometimes calculated from sample weight and knowledge of average density. Boyle's law is often used with helium as the gas to measure grain volume. This method is relatively fast, and is reliable on clean and dry samples.

The measurement may also be based on the loss in weight of a saturated sample immersing in a liquid.

Another method is to crush a dry and clean core sample. The volume of crushed sample is then estimated by immersing cuttings in a suitable liquid.

2.3 Review of Methods of Determining Porosity from Cuttings

2.3.1 Early Technique of Measurement

About seventy years ago, a technique was presented for obtaining porosities of consolidated formations from drill cuttings. The technique provided a means of measuring the bulk volume of a great number of particles, such as drill cuttings. By using a single-unit arrangement of capillary diaphragm (Figure 2.1), the surplus surface liquid from saturated cuttings having pores of capillary size can be removed. This method is relatively accurate and reduces errors present in former solutions to measure the porosity of drill cuttings (Westbrook and Redmond 1946).

Figure 2.1 Apparatus used in determination of porosity of drill cuttings (Westbrook and Redmond 1946)

In this paper, a detailed procedure was devised to achieve the goal and the accuracy of the method was demonstrated by the results of comparative measurements between cores and artificial cuttings. Firstly, the porosity of sandstone and limestone core samples with bulk volume of 4 to 5 cm³ was determined. Then the samples were crushed to a particle size on the basis of that of the cuttings that would normally circulate to the surface. For obtaining large enough size of cuttings, a No. 6 gauge screen (3.35 mm) was used to wash those samples. The porosity of the particle retained on the screen was measured by applying proposed method. The results from the two porosity measurements of cores and cuttings show that the average deviation was 3.3 percent of the porosity.

The method described above is a good but not an excellent way of measuring

porosity of cuttings. From the research, we can learn an evaluation method that can demonstrate the accuracy of the devised procedures: comparing the measurement results from core samples and crushed cuttings. Because it is simple to determine accurate porosity from cores by using conventional analysis methods and this value could be used as a reference data. In order to increase the accuracy, the method needs to be improved and the factors that may cause and affect the differences are also necessary to be analyzed and considered. For instance, during the drilling operation, the cuttings are obtained in various sizes. It is impossible to collect enough cuttings in an expected size from all the interest zones. Therefore, the size of cuttings may have an influence on the estimation of porosity and should be considered as the factor of importance.

2.3.2 CT-scan Method

Nowadays, it is possible to extract density and porosity data from cuttings by application of various laboratory instruments (Siddiqui et al. 2005). Lots of advanced tools and techniques are available to analyze cuttings. In this study, full characterization of a carbonate core plug was conducted using laboratory tools and then crushing the plug into cuttings with different mesh sizes. Cutting samples were then scanned with a CT-scanner, and bulk densities and porosities were determined using advanced histogram-based analysis techniques. The results calculated from cuttings were compared with those for the core plug. The paper introduced the application of micro-CT, Environmental Scanning Electron Microscope (ESEM), Nuclear Magnetic Resonance (NMR) spectrometer and Apparatus for Pore Examination (APEX) mercury porosimeter on analysis of cuttings. Those techniques provide supplementary data on the same cutting samples which were used for comparison. Based on the images generated from micro-CT (Computerized Tomography) and image processing of SEM, the value of porosity could be obtained by using developed procedures. The proposed methodology can be summarized in four steps:

1. Determine the density and porosity of a prepared core plug by using conventional core analysis and CT-based techniques.
2. Crush the plug into cuttings of different mesh sizes and keep separately.
3. Applying CT to scan the cuttings, calculate values of density and porosity and compare against those from plug.
4. Based on various laboratory tools, conduct further analysis of cuttings and compare the results.

From this study, the conclusions reveal that good porosity data can be measured from ESEM micrographs and micro-CT slices using the devised procedures. Additionally, the study showed that the porosity of cuttings of size large than 2.5 mm (8 Mesh or larger) can be measured by using a typical medical-based CT-scanner. For those smaller than 2.5 mm, micro-TC technique was required to obtain accurate porosity data. It can be seen that the size of cuttings is a critical factor that would affect the accuracy of a method. Although the techniques described in the study provide a good way of measuring porosity of cuttings, the achievement of the objective needs substantial support of advanced hardware and software, such requirements may cause the difficulty of extensive use. Therefore, an economical and practical method is still needed to be explored for measuring porosity of cuttings.

2.3.3 IFP Method

Review of published works on porosity determination on cuttings, standard methods similar to the methods used in conventional core analysis have been concluded and discussed by Meazza et al. 1996. Also, the porosity data from cuttings can be obtained by using a medical based CT-scan as described in previous section. The main conclusion of all these studies shows that the accuracy become poor for the cuttings with the diameter lower than 2.5mm. In order to obtain reliable porosity from cutting with the sizes down to 0.5mm, Lenormand and Fonta 2007 tested most of the existing approaches and generated the following conclusions:

- By applying an apparatus designed for small volumes, the volume of solid and grain density determined by helium expansion can be measured accurately. As the grain density is generally available, such measurement is not a necessary step. Even though the mineralogy is unknown, using an average for calculation cannot cause a significant error on results.
- The estimation of bulk volume is not precise enough by employing mercury porosimetry. The reason is that large surface effects give rise to a difficult determination of entry pressure.
- Using power compaction causes large errors on the estimation of bulk volume. Because of the power and the cuttings form “vaults”, it can prevent the uniform compaction of the power.
- As a consequence, the determination of porosity must use pore volume by a saturation method. For the cuttings with sizes smaller than 1mm, the amount of liquid remained by capillary between the cuttings is very large. And two solutions are available to deal with the interstitial liquid: measure the volume by using NMR technique; remove by using a method without removing the liquid inside the cuttings.

Several improved methods for measuring the pore volumes of the cuttings are listed below:

1. Removing the interstitial liquid

By using approaches based on the control of capillary pressure, the purpose of removing the interstitial liquid can be achieved. Before applying these methods, the first step is saturating the cuttings samples with water (or other liquid) under vacuum conditions and room temperature. Then remove the water remained on the outer surface of individual cutting fragments after the saturation process.

- a) Sponge: Place the saturated cuttings on a wet sponge tissue and take a second wet sponge tissue on the surface of the cuttings. Press the top sponge with

hands for several seconds. In order to remove only the liquid between the spaces of cuttings, it is important and necessary to use a wet sponge which has no excess of liquid. A dry sponge with strong absorbent would remove the liquid inside the cuttings. The operation of this method is simple and quick which generates good results for cuttings with diameter size down to 2 mm. For smaller size, the method is less effective since the cuttings enter into the pores on the surface of sponges and are difficult to separate. Therefore, additional material should be considered and combined with sponge to solve this problem.

The grain volume can be estimated by using the average grain density of the dominant lithology. Therefore, the value of porosity can be calculated based on Equation 2.4.

$$\phi = \frac{\left(\frac{W_s - W_d}{\rho_{\text{fluid}}} \right)}{\left(\frac{W_s - W_d}{\rho_{\text{fluid}}} \right) + \frac{W_d}{\rho_{\text{ma}}}} \quad (2.4)$$

Where W_s is the weight of saturated cuttings, W_d is the weight of dry cuttings, ρ_{fluid} is the saturated fluid density, ρ_{ma} is the average grain density.

b) Centrifuge: In order to minimize the capillary end effect, the cuttings samples are placed in small tubes on a porous sponge and keep the height of cuttings about 1 cm. Then calculate the speed to allow an entry capillary pressure around 10 mbar that amounts to liquid meniscus with radius of curvature about 10 microns. Test the efficiency of the removal by applying NMR T2 distribution. The process of this method is slow and takes approximately one week to reach equilibrium.

c) Porous plate: With a more controlled capillary pressure, the principle of this method is similar as the sponge. The saturated cuttings are placed in a tube on a high permeability porous material. We choose the material of alumina Aerolith A10 which is about 10 Darcy with a Pc curve showing a plateau about 20 mbar. The removal of the interstitial liquid is using vacuum through the plate which can also

partially desaturate the plate. With a controlled capillary pressure that corresponds to the plateau of the Pc curve, the porous plate would absorb the remaining interstitial liquid. When the removal of excess water is finished, the cuttings become loose and are almost like dry samples. This method can distinguish the liquid inside the pores from the bulk liquid between the cuttings. The tests show that this porous plate method can generate accurate results and is faster than the centrifuge.

2. Saturation by NMR

Research has found that the total intensity of the NMR signal is proportional to the number of protons. The liquid mass can be measured after calibration with a known mass of liquid. A Maran spectrometer with 23 MHz frequency and 18 mm probe is used as the NMR apparatus. This apparatus can provide the accuracy of the order of 1 mg.

Figure 2.2 Principle of the NMR porosity measurement on cuttings (Lenormand and Fonta 2007)

The relaxation time of the liquid remaining between the cuttings is presented

longer than that inside the cuttings. The figure 2.2 (a) expresses the measured T2 distribution from saturated cuttings: the first peak that has a lower value of T2 represents the liquid entering into the cuttings; the second corresponds to the liquid between the cuttings. For T2 distribution, the areas below the two peaks (the green area in Figure 2.2) are proportional to the volumes of liquid inside and outside the cuttings. Such information can be used to estimate the pore volume of the cuttings. In this test, one and two drops of water (Figure 2.2 b and c) have been added separately to the samples to demonstrate the accuracy of the apparatus. The application of NMR method is mainly to control the efficiency of methods that are based on capillary desorption.

2.4 Review of Methods of Permeability Measurements from Cuttings

When a new production well drilled, the main concerns of operating companies are the reserves and the well deliverability which is directly impacted by rock petrophysical properties. Although a good estimate of porosity and saturation along the well is available from the logs, the evaluation of permeability is more difficult to obtain because this parameter refers to the ability of reservoir rock to transmit fluids (Egermann et al. 2005).

The permeability data are usually obtained by routine analysis at field or laboratory. Core analysis is one of the most reliable techniques to determine permeability while with the disadvantages of high cost and time consuming. An average value of permeability could be obtained by well testing which gives information on the extension and the connectivity of the reservoir. By applying the Modular Dynamics Tester (MDT) technique, a more accurate permeability data can also be achieved. The NMR log is now widely used to provide a fast estimation of the permeability profile along the wells.

The cuttings are generally used by mud loggers to establish the “master log”, in which the geological characterization of the drilled formation is reported. Hydrocarbon indices are also generated from cuttings to identify the reservoir levels. It

is easy to collect cuttings rock material which is coming directly from the formation, but there are few applications of permeability description presented in the literature. The published works on estimation of permeability from cuttings can be divided into two categories namely direct and indirect evaluations.

2.4.1 Direct Permeability Estimation Methods from Cuttings

Though few methods exist to measure directly permeability from cuttings, one of them is proposed by Santarelli et al. 1998. To achieve such a measurement, the cuttings were imbedded into thin disks of acrylic resin and align the cuttings with their larger size. Place the grinding machine on the surface of disk which was used to uncover the cuttings on the two sides of the disk. At this step, the cutting surface was measured either manually by using transparent millimetric paper or automatically with an image analyzer.

Then a special cell named Marcel was used which allowed liquids, such as gas or water, to flow through the disk (Figure 2.3). The flow only exists through the open cuttings because the resin is completely impermeable. With the information of flow rate and the upstream and downstream pressures, the permeability could be measured. Such measurement method is similar with a real core sample. While in order to create a permeable medium, the thickness of the disk must be less than the size of the cuttings.

Another method is on the basis of gas pressure diffusion which was proposed by Luffel 1993. Firstly, place the cleaned and dried cuttings in a cell at atmospheric pressure. Then connect the cell with another cell under pressure, record the decrease of the pressure and interpret in term of permeability. Applying gas instead of liquids, the principle of such method is similar to well testing. However, this method is only suitable for rocks with extra low permeabilities (less than 0.01 mD) due to the low viscosity of gases.

Figure 2.3 Diagram of the cell “Marcel” to measure permeability on cuttings (Santarelli et al. 1998)

2.4.2 Indirect Permeability Estimation Methods from Cuttings

For such category of measuring methods, the value of permeability is generated using empirical correlations with properties which are related to pore connectivity, pore size distribution or the spatial correlation between the pores. And these parameters are generally estimated from capillary properties, by NMR or image analysis.

There are couples of methods which have been proposed to derive permeability based on mercury porosimetry curves (Purcell 1949; Thomeer 1960; Swanson 1981; Thomeer 1983). From the comparison between these approaches made by Kamath, it shows that the best result is achieved with new correlations based on the Swanson characteristic length (Kamath 1992). In addition, a possible use of mercury porosimetry curves generated from cuttings is also presented by Kamath and Swanson.

Although lots of papers have been published on the permeability determination from NMR measurements, not too much refer to application on cuttings. In this field, Chevron made an effort to solve the problem. They designed a prototype equipment which applied to rig conditions (Nigh and Taylor 1984). After cleaning and drying the cuttings samples, place them in a portable NMR tool. The permeability is estimated

from the whole T_2 relaxation signal using the Timur law (Timur 1968). In recent years, this method has been improved and a commercial apparatus is invented (Mirotchnik et al. 2004). The developed technology can obtain NMR petrophysical parameters both at the well and in the laboratory. For multi-saturated cuttings and core plugs from clastic formations, the NMR permeability can be estimated by using a new developed model in their work.

The permeability data can also be evaluated through a thin section obtained from cuttings using image analysis. The value is derived from empirical law (Coskun and Wardlaw 1993, Ioannidis et al. 1996) or from Carman-Kozeny laws.

Recently, an integrated pore-scale modeling procedure is investigated and used to determine petrophysical properties of cuttings by Mock et al., 2007. Their approach is based on reestablishing digital three-dimensional models of reservoir rocks with input data gathered from drill cuttings. By combining X-ray diffraction analysis, sieving, image analysis and data from wireline logs, relevant input data numerical rock models can be obtained. According to the paper, the procedure mainly includes three steps:

1. With data obtained from thin section images, generate 3D numerical rock models;
2. According to the grid representative of the rock model, calculate petrophysical properties on samples;
3. By using network modeling techniques, extract pore network and calculate multiphase flow properties.

This study suggests that integrated pore-scale modeling presents excellent possibilities for determination reservoir rock properties from drill cuttings: NMR relaxation, electrical resistivity and multiphase flow properties were calculated from the reconstructed models; estimated permeabilities agree reasonably well with measured data.

2.4.3 The Liquid Pressure Pulse Method

This method is originally proposed by IFP (Egermann et al. 2005) which is to obtain an effective flow inside the cuttings by compression of residual gas initially trapped into them. In order to minimize the diffusion of pressure into the rock, a viscous liquid is used as displacing fluid. This approach is fit for values of permeability corresponding to reservoir rocks which are not available from gas pressure test.

The experimental apparatus shown in figure 2.4 is very simple. It is mainly composed of a cell containing a few volumes of cuttings and a pressure cell including a bellow coupled to a spring and a pressure sensor. All the apparatus is full of the liquid which is injected under pressure with a pump.

Figure 2.4 Schematic of the Liquid Pressure Pulse Apparatus (Lenormand and Fonta 2007)

Firstly, the cleaned and dried cuttings are saturated with the viscous oil by spontaneous imbibitions in a beaker. At the end of such process, there remains some gas trapped inside the cuttings as disconnected gas. Then place these cuttings into cuttings cell that is then connected to the pressure cell. The viscous oil flows into the cuttings and compresses the trapped air. During the process of displacement, the pressure is monitored and the volume of liquid entering into the cuttings is obtained from the scale on the bellow and spring system. The rate of invasion is determined by

the fluid viscosity and the rock permeability.

The value of permeability can be derived using a numerical model on the basis of the correlations describing that a viscous liquid enters into a compressible medium of spherical geometry. This model is similar to a well test with spherical instead of cylindrical geometry.

CHAPTER III

METHODOLOGY

From the review of methods on measuring porosity of cuttings, the procedure presented by IFP has the advantages of being economical, saving time and being easy to operate. Therefore, the approach applied in this project will be improved on the basis of IFP's method to measure the porosity from cuttings.

This thesis project presents an evaluation of the improved method by comparing cuttings porosity measurement to porosity measurements from core plugs with three different permeabilities. Since the estimation of bulk volume is not practically possible for cutting samples, the measurement of porosity of cuttings depends on the two remaining parameters, the grain volume V_g and the pore volume V_p . According to the procedure presented by IFP, the grain volume is calculated from the weight of dried cuttings, applying an average grain density. As an improved point, we will use more accurate values of grain density which obtained from conventional core analysis for measuring cuttings porosity. Such improvement can minimize the errors of the original method and generate a better analysis of results. Additionally, the pore volume is obtained from the saturation method adapted to cuttings.

The principal procedures used for this project can be summarized as follows:

1. Prepare core plugs and cutting samples.
2. Measure the grain density, porosity and permeability of core plugs by using conventional core analysis.
3. Separate the cuttings crushed from plugs into four mesh sizes and store each group separately.
4. Calculate porosity of cuttings in different sizes by using the improved IFP method.
5. Compare the porosity values from cuttings and cores, evaluate and do error

analysis on the applied method.

3.1 Samples Preparation

In the laboratory, we accessed core plugs with a 1.5 inch diameter and 7 inches length (Figure 3.1a). We chose three core plugs with different values of permeability as our study samples.

For each core plug, we cut down both ends and polished them further. After being cut and trimmed, the cores became wet and dirty. These cores needed to be cleaned and then dried using ventilation first and then an oven at 60 to 70° Cesium for a minimum of 10 hours. The prepared six cores were to be used for measuring grain density and reference porosity data. We crushed the remaining center section using a hammer and produced the artificial drill cuttings (Figure 3.1b). The further screening work for the cuttings will be introduced in Section 3.3.

Figure 3.1 Core Plug and Samples Preparation Diagram

3.2 Effective Porosity and Grain Density Determination on Cores

3.2.1 Description

In this study, the effective porosity of core samples is obtained by measuring the bulk volume and the grain volume. The grain density can be determined by the weight of dry samples and grain volume.

Due to the cores being prepared as perfect cylinders, their bulk volume can be calculated from their diameters and heights. The measurement of grain volume can be achieved by using the gas expansion method. So the equipments used are vernier caliper, electronic balance, and helium porosimeter.

The helium porosimeter uses the principle of gas expansion, as described by Boyle's Law, and measures the grain volume. The gas expansion does not concern the solid volume but only the pore volume so that the solid volume can be deducted from the pressure measurements. Therefore, it is necessary to carry out a precise calibration of the volumes of the apparatus. Any gas can be used, but in some situations, helium is the primary choice other than nitrogen because of some condensation process. Using a helium porosimeter we will take three pairs of pressure readings with each pair associated with an initial reference volume and an expansion from the reference volume into the core holder. Figure 3.2 shows a schematic of the helium porosimeter used for this experiment.

In this project, we are going to study three groups of core plugs. Each group includes two core plugs that should have similar properties with the intent to ensure the accuracy of the results. The difference among each group is the different values of permeabilities. Table 3.1 shows the name of each core plug. For each, we will operate the measurement procedure, as explained in the following sections.

Figure 3.2 Helium Porosimeter

Table 3.1 Name of Core Plugs Samples

Sample No.	Core Name
1	C1_1
2	C1_2
3	C2_1
4	C2_2
5	C3_1
6	C3_2

3.2.2 Procedure for Measuring Bulk Volume

1. Weigh the dry sample using the electronic balance and record its weight, W_d , on the data sheet.
2. Open the jaws of the vernier caliper and take three length readings of the core plug at three different locations. Record the measurements on the data sheet and calculate their average length, L .

3. Measure the diameter three times, each time at a different location. Record the measurements on the data sheet and calculate their average diameter, D .
4. Calculate the bulk volume, V_b , and record on the data sheet.

3.2.3 Procedure for Measuring Grain Volume

1. Turn on the valve of the helium cylinder.
2. Place the core holder (with all of the billets inside of it) on the recessed platform and make sure that the holder does not move.
3. Turn the load valve (front bottom) all the way from the right to the left in order to elevate the platform and seal the holder.
4. Turn the top left valve which should be facing away from the gage, to the left to the open position. This allows pressure to increase.
5. When the pressure reaches between 90-100 psi, turn the valve to its previous position and allow the pressure to stabilize. The scale reading is P_{IL} , which should be recorded on the data sheet.
6. Turn the expansion valve, which should be facing away from the gage, towards the gauge to the open position. This allows the helium to expand inside the core holder. Thus the pressure will decrease and stabilize at a lower value. This pressure reading is P_{fI} .
7. Turn the expansion valve away from the gage to release the pressure.
8. Release the load valve and push down the core holder so that the platform is recessed again. Remove the core holder.
9. Remove the billet with the mark **C** on it. The volume of the billet **C** is given as V_c . The volume can be obtained from the chart given in the table below.
10. Repeat steps 2 through 8. The higher and lower stabilizing pressures of the given data sheet are P_{I2} and P_{f2} , respectively.

11. Remove billets from the core holder and match the height of the core with the billets.
12. Place the core inside the holder and put the remaining billets (other than the ‘matched’) on top of it. Here it should be noted that the top surface of the billet should not go above the holder.
13. The total volume of the billets outside the core is represented as $\Sigma V_{billets\_left}$.
14. Repeat the steps 2 through 8. The pressures are P_{i3} and P_{f3} respectively.
15. Put all the billets inside the holder for the next group to perform the test.
16. Calculate the reference volume, V_r , and grain volume, V_g using the calculation procedure given below.
17. Operate the above procedures three times to obtain the average porosity.
18. Use data from Table 3.2 for the calculations.

Table 3.2 Dimensions of the Billets Used

Billets	Length, cm	Diameter, cm	Volume, cm ³
A	0.3150	3.8050	3.5801
B	0.9375	3.7730	10.4765
C	1.2550	3.7810	14.0840
D	1.9025	3.7805	21.3448
E	2.8475	3.7825	32.9809

3.2.4 Calculations

1. Calculation of bulk volume

$$V_b = \left(\pi \bar{D}^2 \bar{L} \right) / 4 \quad (3.1)$$

2. Calculation of reference volume

$$V_r = \frac{P_{f1} P_{i2} V_c}{P_{f1} P_{i2} - P_{f2} P_{i1}} \quad (3.2)$$

3. Calculation of grain volume

$$V_g = \sum V_{\text{billets\_left}} + \left(\frac{P_{i1}}{P_{f1}} - \frac{P_{i3}}{P_{f3}} \right) \cdot V_r \quad (3.3)$$

4. Calculation of pore volume from Helium porosimeter

$$V_p = V_b - V_g \quad (3.4)$$

5. Calculation of effective porosity

$$\phi = V_p / V_b \quad (3.5)$$

6. Calculation of grain density

$$\rho_g = W_d / V_g \quad (3.6)$$

3.3 Determination of Permeability on Cores

We will estimate the permeability of core samples by using Darcy's Law and applying the gas permeameter shown in Figure 3.3.

Figure 3.3 Gas Permeameter

3.4 Method of Estimation the Porosity of Cuttings

The measurement of porosity from cuttings is going to rely on the solid volume (or grain volume V_g) and the pore volume V_p . The volume of solid is calculated from the weight of dry cuttings and grain density is generated from the corresponding core sample analysis. The pore volume is measured by the saturation method adapted to cuttings. The whole procedure of the applied method is presented in the following sections.

3.4.1 Screening Cutting Samples

In previous part we have introduced the preparation of artificial cutting samples by using a hammer crush the core plug. Since the size of cuttings may have significance influence on the measured porosity data, we divide the cleaned and dried crushed cuttings into four different sizes on the basis of diameter by using mesh. Table 3.3 shows the definition of the four sizes. All the three prepared cutting samples needed to be processed to obtain artificial cutting in different sizes. Then put each sample in a small plastic bag and label number. So we can get twelve bags totally. We keep them at room temperature and clean area for the further work.

The samples are named after the number of crushed core plugs and their sizes. For example, C1_B means that the cuttings are crushed from the #1 core plug and with the diameter between 0.85 and 2.00 mm.

Figure 3.4 Pre-crushed cuttings for screening

Table 3.3 Size Definition of Cuttings

No.	Size Name	Minimum, mm	Maximum, mm
1	A	0.425	0.850
2	B	0.850	2.000
3	C	2.000	2.800
4	D	2.800	4.000

3.4.2 Water Saturation

Firstly, prepare a bottle for each bag and put the cuttings into it. The bottles filled with cuttings are placed in a cleaned and empty tank with lid which connected to a vacuum pump. We keep the pump on for five hours and the pressure inside the cell will drop. Next, use a pipe to connect the tank and a container filled with water, so water can flow into the tank and saturate the cuttings. Once the cuttings covered with water, close all the valves on the tanks. The saturation process should last 36 hours to make sure water fully penetrate the pores of cuttings.

3.4.3 Removal of Excess Water from Cuttings

To obtain accurate and reproducible porosity measurement, removing the water excess from the outer surface of individual cutting fragments is a critical step. In Chapter II, we reviewed several methods provided by IFP to achieve this goal. The technique that was selected in this study is as follows:

After the saturation period, take one bottle from the water tank and pour out the existing water. Then spread the cutting fragments on a wet sponge and place a second wet sponge on top of the cuttings and press this with a hand for thirty seconds. In order to remove only the interstitial liquid, it is necessary to use a wrung-out wet sponge. A dry sponge with strong absorbance may remove the liquid inside the cuttings, which would cause an underestimation of pore volume.

For smaller cuttings (less than 2 mm), this method is difficult to operate since the cuttings easily enter the sponge. In order to solve this problem, put a wet paper towel on the top of the wet sponge and place the saturated cuttings on the wet paper towel. Then place the second wet sponge with another wet paper towel on the surface of the cuttings and press with hands. After removing the interstitial water from cuttings, collect them in a glass container and prepare for the next step. Other cutting samples should be kept saturated in water bottles until all the work is finished on one sample.

Figure 3.5 Removing the liquid covering the cuttings with size larger than 1 mm

Figure 3.6 Removing the liquid covering the cuttings with size less than 1 mm

3.4.4 Obtaining the Pore Volume

After we used wet sponge to remove the excess water between the cuttings, there still remains extra water outside of cuttings. We found that the saturated weight of a sample decreases obviously with time. This is due to the fact that the amount of water between cuttings is easy to lose into air because such water direct contact with air. Therefore, time is important to weigh the saturated samples. A smaller time than necessary leaves excess water between cuttings. A larger time than necessary causes extra water loss. Therefore, we will study the change of the weight of saturated cuttings on time.

For each sample, we put the saturated cuttings in a glass container. Then place it on the top of a balance for 2 hours, and record its weight per 5 minutes on data sheet. After drying in a ventilated oven at 100° Celsius, the cuttings can be weighted. Given the density of the saturating fluid at the temperature of the laboratory, the pore volume can be calculated by using following equation:

$$V_p = \frac{W_s - W_d}{\rho_{\text{fluid}}} \quad (3.7)$$

3.4.5 Obtaining the Grain Volume and Porosity

The volume of grain is obtained from the grain density using the following relation:

$$V_g = \frac{W_d}{\rho_g} \quad (3.8)$$

The porosity is calculated using V_p and V_g as follows:

$$\phi = \frac{V_p}{V_p + V_g} \quad (3.9)$$

CHAPTER IV

RESULTS AND ANALYSIS

In this chapter, all experimental data are presented, and values of porosity from core plugs and artificial cutting samples are generated based on the measurement procedures described in the previous chapter. Through comparison of porosity data determined in two ways, we are going to analyze results and evaluate the accuracy of the improved IFP method.

4.1 Effective Porosity and Grain Density Data Measured from Core Plugs

4.1.1 Data Obtained from Equipments

By using a vernier caliper, the diameter and length of each core sample are measured three times at different locations (Table 4.1). We will take average values for the calculation of bulk volume.

Table 4.1 Dimensions of Core Plugs Data Sheet

Sample	Item	Rd #1	Rd #2	Rd #3	Avg.	Unit
C1_1	Diameter	3.8175	3.8075	3.8100	3.8117	cm
	Length	5.3325	5.3250	5.3425	5.3333	cm
C1_2	Diameter	3.8225	3.8175	3.8100	3.8167	cm
	Length	5.7200	5.7250	5.7150	5.7200	cm
C2_1	Diameter	3.8100	3.8000	3.8175	3.8092	cm
	Length	5.6825	5.6875	5.7025	5.6908	cm
C2_2	Diameter	3.8200	3.8175	3.8150	3.8175	cm
	Length	6.0125	6.0100	6.0000	6.0075	cm
C3_1	Diameter	3.8075	3.7525	3.7825	3.7808	cm
	Length	4.7475	4.7250	4.7325	4.7350	cm
C3_2	Diameter	3.7700	3.7825	3.8050	3.7858	cm
	Length	4.7375	4.7450	4.7500	4.7442	cm

Following the procedure of measuring grain volume described in Section 3.2.3, the pressure data are measured by applying helium porosimeter (Table 4.2). Based on these data, the reference volume and grain volume for each core sample can be calculated.

Table 4.2 Pressure Data Record Sheet

Pressure Data:		Rd #1	Rd #2	Rd #3	Unit
With all billets	P_{i1}	99.1	98.2	97.8	psig
	P_{f1}	84.2	83.4	82.9	psig
With all but No. C billets	P_{i2}	97.9	99.1	98.6	psig
	P_{f2}	61.9	62.5	62.1	psig
With sample C1_1	P_{i3}	98.9	99.0	98.4	psig
	P_{f3}	66.9	66.9	66.6	psig
With sample C1_2	P_{i3}	98.6	99.0	99.5	psig
	P_{f3}	65.5	65.7	66.0	psig
With sample C2_1	P_{i3}	99.3	99.2	98.6	psig
	P_{f3}	65.9	66.0	65.6	psig
With sample C2_2	P_{i3}	98.2	98.3	99.0	psig
	P_{f3}	65.2	65.3	65.9	psig
With sample C3_1	P_{i3}	98.8	98.2	99.4	psig
	P_{f3}	65.2	64.8	65.4	psig
With sample C3_2	P_{i3}	99.5	99.2	98.1	psig
	P_{f3}	67.7	67.3	66.7	psig

4.1.2 Calculated Results

According to equations listed in Section 3.2.4, the values of effective porosity and grain density measured from six core samples are shown in Table 4.3. Since every two cores of the six were cut from the same core plug, we will take the average value as the reference data.

Table 4.3 Calculated Data Sheet

Sample	W_d (g)	V_b (cm ³)	V_g (cm ³)	ρ_g (g/cm ³)	ϕ_e	Avg. ρ_g (g/cm ³)	Avg. ϕ_e
C1_1	135.6535	60.8581	49.7211	2.7283	0.1830	2.7193	0.1909
C1_2	142.1103	65.4417	52.4312	2.7104	0.1988		
C2_1	142.7107	64.8523	52.5100	2.7178	0.1903	2.7150	0.1874
C2_2	152.0971	68.7609	56.0802	2.7121	0.1844		
C3_1	112.0319	53.1600	41.5985	2.6932	0.2175	2.7040	0.2046
C3_2	117.1954	53.4039	43.1695	2.7148	0.1916		

4.2 Permeability Measured from Core Plugs

The calculated results are shown in Table 4.4.

Table 4.4 Cores Permeability Data

No.	Core Sample	Permeability, mD
1	C1	47
2	C2	82
3	C3	192

4.3 Porosity Measured from Artificial Cuttings

The cuttings were crushed from core plugs with three different permeabilities. For each kind of crushed cuttings, they had been sieved in four various size intervals by using mesh of which the diameter range from 0.425 to 4.000 mm. Therefore, the values of porosity are going to be measured from twelve cutting samples. According to the estimation measurements mentioned in Section 3.3, we monitored the weight of saturated cuttings over time, and then converted such data into porosity. The recorded and calculated data for each cutting samples are shown in Tables 4.5 to 4.16.

Table 4.5 Measured Porosity Data over Time for Sample C1_A

No.	Time (min)	Saturated Weight (g)	Dry Weight (g)	Pore V (cm ³)	Grain V (cm ³)	Porosity
1	0	9.0708	7.9946	1.0762	2.9399	0.2680
2	5	9.0286	7.9946	1.0340	2.9399	0.2602
3	10	8.9923	7.9946	0.9977	2.9399	0.2534
4	15	8.9547	7.9946	0.9601	2.9399	0.2462
5	20	8.9183	7.9946	0.9237	2.9399	0.2391
6	25	8.8816	7.9946	0.8870	2.9399	0.2318
7	30	8.8452	7.9946	0.8506	2.9399	0.2244
8	35	8.8096	7.9946	0.8150	2.9399	0.2171
9	40	8.7741	7.9946	0.7795	2.9399	0.2096
10	45	8.7390	7.9946	0.7444	2.9399	0.2020
11	50	8.7013	7.9946	0.7067	2.9399	0.1938
12	55	8.6658	7.9946	0.6712	2.9399	0.1859
13	60	8.6298	7.9946	0.6352	2.9399	0.1777
14	65	8.5954	7.9946	0.6008	2.9399	0.1697
15	70	8.5609	7.9946	0.5663	2.9399	0.1615
16	75	8.5268	7.9946	0.5322	2.9399	0.1533
17	80	8.4908	7.9946	0.4962	2.9399	0.1444
18	85	8.4564	7.9946	0.4618	2.9399	0.1358
19	90	8.4231	7.9946	0.4285	2.9399	0.1272
20	95	8.3890	7.9946	0.3944	2.9399	0.1183
21	100	8.3547	7.9946	0.3601	2.9399	0.1091
22	110	8.2910	7.9946	0.2964	2.9399	0.0916
23	120	8.2242	7.9946	0.2296	2.9399	0.0724

Table 4.6 Measured Porosity Data over Time for Sample C1_B

No.	Time (min)	Saturated Weight (g)	Dry Weight (g)	Pore V (cm ³)	Grain V (cm ³)	Porosity
1	0	14.2239	12.7552	1.4687	4.6905	0.2385
2	5	14.1913	12.7552	1.4361	4.6905	0.2344
3	10	14.1582	12.7552	1.4030	4.6905	0.2302
4	15	14.1248	12.7552	1.3696	4.6905	0.2260
5	20	14.0912	12.7552	1.3360	4.6905	0.2217
6	25	14.0569	12.7552	1.3017	4.6905	0.2172
7	30	14.0220	12.7552	1.2668	4.6905	0.2126
8	35	13.9872	12.7552	1.2320	4.6905	0.2080
9	40	13.9525	12.7552	1.1973	4.6905	0.2034
10	45	13.9175	12.7552	1.1623	4.6905	0.1986
11	50	13.8834	12.7552	1.1282	4.6905	0.1939
12	55	13.8487	12.7552	1.0935	4.6905	0.1891
13	60	13.8137	12.7552	1.0585	4.6905	0.1841
14	65	13.7789	12.7552	1.0237	4.6905	0.1791
15	70	13.7445	12.7552	0.9893	4.6905	0.1742
16	75	13.7090	12.7552	0.9538	4.6905	0.1690
17	80	13.6741	12.7552	0.9189	4.6905	0.1638
18	85	13.6396	12.7552	0.8844	4.6905	0.1586
19	90	13.6063	12.7552	0.8511	4.6905	0.1536
20	95	13.5727	12.7552	0.8175	4.6905	0.1484
21	100	13.5395	12.7552	0.7843	4.6905	0.1433
22	110	13.4716	12.7552	0.7164	4.6905	0.1325
23	120	13.3999	12.7552	0.6447	4.6905	0.1208

Table 4.7 Measured Porosity Data over Time for Sample C1_C

No.	Time (min)	Saturated Weight (g)	Dry Weight (g)	Pore V (cm ³)	Grain V (cm ³)	Porosity
1	0	16.6850	15.0461	1.6389	5.5330	0.2285
2	5	16.6478	15.0461	1.6017	5.5330	0.2245
3	10	16.6161	15.0461	1.5700	5.5330	0.2210
4	15	16.5812	15.0461	1.5351	5.5330	0.2172
5	20	16.5470	15.0461	1.5009	5.5330	0.2134
6	25	16.5132	15.0461	1.4671	5.5330	0.2096
7	30	16.4791	15.0461	1.4330	5.5330	0.2057
8	35	16.4456	15.0461	1.3995	5.5330	0.2019
9	40	16.4111	15.0461	1.3650	5.5330	0.1979
10	45	16.3761	15.0461	1.3300	5.5330	0.1938
11	50	16.3406	15.0461	1.2945	5.5330	0.1896
12	55	16.3030	15.0461	1.2569	5.5330	0.1851
13	60	16.2662	15.0461	1.2201	5.5330	0.1807
14	65	16.2310	15.0461	1.1849	5.5330	0.1764
15	70	16.1970	15.0461	1.1509	5.5330	0.1722
16	75	16.1617	15.0461	1.1156	5.5330	0.1678
17	80	16.1268	15.0461	1.0807	5.5330	0.1634
18	85	16.0915	15.0461	1.0454	5.5330	0.1589
19	90	16.0577	15.0461	1.0116	5.5330	0.1546
20	95	16.0239	15.0461	0.9778	5.5330	0.1502
21	100	15.9909	15.0461	0.9448	5.5330	0.1459
22	110	15.9257	15.0461	0.8796	5.5330	0.1372
23	120	15.8607	15.0461	0.8146	5.5330	0.1283

Table 4.8 Measured Porosity Data over Time for Sample C1_D

No.	Time (min)	Saturated Weight (g)	Dry Weight (g)	Pore V (cm ³)	Grain V (cm ³)	Porosity
1	0	18.9010	17.1710	1.7300	6.3144	0.2151
2	5	18.8659	17.1710	1.6949	6.3144	0.2116
3	10	18.8365	17.1710	1.6655	6.3144	0.2087
4	15	18.8096	17.1710	1.6386	6.3144	0.2060
5	20	18.7829	17.1710	1.6119	6.3144	0.2034
6	25	18.7569	17.1710	1.5859	6.3144	0.2007
7	30	18.7304	17.1710	1.5594	6.3144	0.1980
8	35	18.7047	17.1710	1.5337	6.3144	0.1954
9	40	18.6782	17.1710	1.5072	6.3144	0.1927
10	45	18.6518	17.1710	1.4808	6.3144	0.1900
11	50	18.6252	17.1710	1.4542	6.3144	0.1872
12	55	18.5969	17.1710	1.4259	6.3144	0.1842
13	60	18.5679	17.1710	1.3969	6.3144	0.1812
14	65	18.5348	17.1710	1.3638	6.3144	0.1776
15	70	18.5101	17.1710	1.3391	6.3144	0.1750
16	75	18.4822	17.1710	1.3112	6.3144	0.1719
17	80	18.4555	17.1710	1.2845	6.3144	0.1690
18	85	18.4265	17.1710	1.2555	6.3144	0.1659
19	90	18.3974	17.1710	1.2264	6.3144	0.1626
20	95	18.3692	17.1710	1.1982	6.3144	0.1595
21	100	18.3397	17.1710	1.1687	6.3144	0.1562
22	110	18.2829	17.1710	1.1119	6.3144	0.1497
23	120	18.2266	17.1710	1.0556	6.3144	0.1432

Table 4.9 Measured Porosity Data over Time for Sample C2_A

No.	Time (min)	Saturated Weight (g)	Dry Weight (g)	Pore V (cm ³)	Grain V (cm ³)	Porosity
1	0	8.7593	7.8314	0.9279	2.8845	0.2434
2	5	8.7256	7.8314	0.8942	2.8845	0.2366
3	10	8.6968	7.8314	0.8654	2.8845	0.2308
4	15	8.6685	7.8314	0.8371	2.8845	0.2249
5	20	8.6388	7.8314	0.8074	2.8845	0.2187
6	25	8.6097	7.8314	0.7783	2.8845	0.2125
7	30	8.5811	7.8314	0.7497	2.8845	0.2063
8	35	8.5508	7.8314	0.7194	2.8845	0.1996
9	40	8.5211	7.8314	0.6897	2.8845	0.1930
10	45	8.4909	7.8314	0.6595	2.8845	0.1861
11	50	8.4609	7.8314	0.6295	2.8845	0.1791
12	55	8.4303	7.8314	0.5989	2.8845	0.1719
13	60	8.3997	7.8314	0.5683	2.8845	0.1646
14	65	8.3691	7.8314	0.5377	2.8845	0.1571
15	70	8.3409	7.8314	0.5095	2.8845	0.1501
16	75	8.3102	7.8314	0.4788	2.8845	0.1424
17	80	8.2793	7.8314	0.4479	2.8845	0.1344
18	85	8.2481	7.8314	0.4167	2.8845	0.1262
19	90	8.2163	7.8314	0.3849	2.8845	0.1177
20	95	8.1849	7.8314	0.3535	2.8845	0.1092
21	100	8.1534	7.8314	0.3220	2.8845	0.1004
22	110	8.0899	7.8314	0.2585	2.8845	0.0822
23	120	8.0302	7.8314	0.1988	2.8845	0.0645

Table 4.10 Measured Porosity Data over Time for Sample C2_B

No.	Time (min)	Saturated Weight (g)	Dry Weight (g)	Pore V (cm ³)	Grain V (cm ³)	Porosity
1	0	12.5188	11.2533	1.2655	4.1449	0.2339
2	5	12.4850	11.2533	1.2317	4.1449	0.2291
3	10	12.4513	11.2533	1.1980	4.1449	0.2242
4	15	12.4174	11.2533	1.1641	4.1449	0.2193
5	20	12.3839	11.2533	1.1306	4.1449	0.2143
6	25	12.3505	11.2533	1.0972	4.1449	0.2093
7	30	12.3178	11.2533	1.0645	4.1449	0.2043
8	35	12.2848	11.2533	1.0315	4.1449	0.1993
9	40	12.2522	11.2533	0.9989	4.1449	0.1942
10	45	12.2198	11.2533	0.9665	4.1449	0.1891
11	50	12.1866	11.2533	0.9333	4.1449	0.1838
12	55	12.1542	11.2533	0.9009	4.1449	0.1785
13	60	12.1212	11.2533	0.8679	4.1449	0.1731
14	65	12.0874	11.2533	0.8341	4.1449	0.1675
15	70	12.0543	11.2533	0.8010	4.1449	0.1620
16	75	12.0210	11.2533	0.7677	4.1449	0.1563
17	80	11.9882	11.2533	0.7349	4.1449	0.1506
18	85	11.9558	11.2533	0.7025	4.1449	0.1449
19	90	11.9243	11.2533	0.6710	4.1449	0.1393
20	95	11.8925	11.2533	0.6392	4.1449	0.1336
21	100	11.8611	11.2533	0.6078	4.1449	0.1279
22	110	11.7966	11.2533	0.5433	4.1449	0.1159
23	120	11.7327	11.2533	0.4794	4.1449	0.1037

Table 4.11 Measured Porosity Data over Time for Sample C2_C

No.	Time (min)	Saturated Weight (g)	Dry Weight (g)	Pore V (cm ³)	Grain V (cm ³)	Porosity
1	0	16.3641	14.7625	1.6016	5.4375	0.2275
2	5	16.3279	14.7625	1.5654	5.4375	0.2235
3	10	16.2929	14.7625	1.5304	5.4375	0.2196
4	15	16.2587	14.7625	1.4962	5.4375	0.2158
5	20	16.2244	14.7625	1.4619	5.4375	0.2119
6	25	16.1924	14.7625	1.4299	5.4375	0.2082
7	30	16.1588	14.7625	1.3963	5.4375	0.2043
8	35	16.1233	14.7625	1.3608	5.4375	0.2002
9	40	16.0882	14.7625	1.3257	5.4375	0.1960
10	45	16.0535	14.7625	1.2910	5.4375	0.1919
11	50	16.0158	14.7625	1.2533	5.4375	0.1873
12	55	15.9774	14.7625	1.2149	5.4375	0.1826
13	60	15.9383	14.7625	1.1758	5.4375	0.1778
14	65	15.9001	14.7625	1.1376	5.4375	0.1730
15	70	15.8610	14.7625	1.0985	5.4375	0.1681
16	75	15.8230	14.7625	1.0605	5.4375	0.1632
17	80	15.7858	14.7625	1.0233	5.4375	0.1584
18	85	15.7508	14.7625	0.9883	5.4375	0.1538
19	90	15.7163	14.7625	0.9538	5.4375	0.1492
20	95	15.6801	14.7625	0.9176	5.4375	0.1444
21	100	15.6440	14.7625	0.8815	5.4375	0.1395
22	110	15.5733	14.7625	0.8108	5.4375	0.1298
23	120	15.5006	14.7625	0.7381	5.4375	0.1195

Table 4.12 Measured Porosity Data over Time for Sample C2_D

No.	Time (min)	Saturated Weight (g)	Dry Weight (g)	Pore V (cm ³)	Grain V (cm ³)	Porosity
1	0	18.5686	16.9315	1.6371	6.2364	0.2079
2	5	18.5417	16.9315	1.6102	6.2364	0.2052
3	10	18.5201	16.9315	1.5886	6.2364	0.2030
4	15	18.4998	16.9315	1.5683	6.2364	0.2009
5	20	18.4796	16.9315	1.5481	6.2364	0.1989
6	25	18.4576	16.9315	1.5261	6.2364	0.1966
7	30	18.4368	16.9315	1.5053	6.2364	0.1944
8	35	18.4163	16.9315	1.4848	6.2364	0.1923
9	40	18.3957	16.9315	1.4642	6.2364	0.1901
10	45	18.3748	16.9315	1.4433	6.2364	0.1879
11	50	18.3537	16.9315	1.4222	6.2364	0.1857
12	55	18.3316	16.9315	1.4001	6.2364	0.1833
13	60	18.3101	16.9315	1.3786	6.2364	0.1810
14	65	18.2885	16.9315	1.3570	6.2364	0.1787
15	70	18.2665	16.9315	1.3350	6.2364	0.1763
16	75	18.2445	16.9315	1.3130	6.2364	0.1739
17	80	18.2223	16.9315	1.2908	6.2364	0.1715
18	85	18.1999	16.9315	1.2684	6.2364	0.1690
19	90	18.1758	16.9315	1.2443	6.2364	0.1663
20	95	18.1524	16.9315	1.2209	6.2364	0.1637
21	100	18.1289	16.9315	1.1974	6.2364	0.1611
22	110	18.0820	16.9315	1.1505	6.2364	0.1557
23	120	18.0350	16.9315	1.1035	6.2364	0.1503

Table 4.13 Measured Porosity Data over Time for Sample C3_A

No.	Time (min)	Saturated Weight (g)	Dry Weight (g)	Pore V (cm ³)	Grain V (cm ³)	Porosity
1	0	8.0709	7.0510	1.0199	2.6076	0.2812
2	5	8.0347	7.0510	0.9837	2.6076	0.2739
3	10	7.9996	7.0510	0.9486	2.6076	0.2667
4	15	7.9647	7.0510	0.9137	2.6076	0.2595
5	20	7.9295	7.0510	0.8785	2.6076	0.2520
6	25	7.8949	7.0510	0.8439	2.6076	0.2445
7	30	7.8609	7.0510	0.8099	2.6076	0.2370
8	35	7.8261	7.0510	0.7751	2.6076	0.2291
9	40	7.7916	7.0510	0.7406	2.6076	0.2212
10	45	7.7570	7.0510	0.7060	2.6076	0.2131
11	50	7.7229	7.0510	0.6719	2.6076	0.2049
12	55	7.6885	7.0510	0.6375	2.6076	0.1964
13	60	7.6543	7.0510	0.6033	2.6076	0.1879
14	65	7.6200	7.0510	0.5690	2.6076	0.1791
15	70	7.5864	7.0510	0.5354	2.6076	0.1703
16	75	7.5517	7.0510	0.5007	2.6076	0.1611
17	80	7.5181	7.0510	0.4671	2.6076	0.1519
18	85	7.4857	7.0510	0.4347	2.6076	0.1429
19	90	7.4526	7.0510	0.4016	2.6076	0.1335
20	95	7.4195	7.0510	0.3685	2.6076	0.1238
21	100	7.3861	7.0510	0.3351	2.6076	0.1139
23	110	7.3206	7.0510	0.2696	2.6076	0.0937
25	120	7.2565	7.0510	0.2055	2.6076	0.0730

Table 4.14 Measured Porosity Data over Time for Sample C3_B

No.	Time (min)	Saturated Weight (g)	Dry Weight (g)	Pore V (cm ³)	Grain V (cm ³)	Porosity
1	0	13.4009	11.7655	1.6354	4.3512	0.2732
2	5	13.3636	11.7655	1.5981	4.3512	0.2686
3	10	13.3268	11.7655	1.5613	4.3512	0.2641
4	15	13.2918	11.7655	1.5263	4.3512	0.2597
5	20	13.2556	11.7655	1.4901	4.3512	0.2551
6	25	13.2195	11.7655	1.4540	4.3512	0.2505
7	30	13.1840	11.7655	1.4185	4.3512	0.2459
8	35	13.1482	11.7655	1.3827	4.3512	0.2411
9	40	13.1129	11.7655	1.3474	4.3512	0.2364
10	45	13.0776	11.7655	1.3121	4.3512	0.2317
11	50	13.0445	11.7655	1.2790	4.3512	0.2272
12	55	13.0087	11.7655	1.2432	4.3512	0.2222
13	60	12.9740	11.7655	1.2085	4.3512	0.2174
14	65	12.9390	11.7655	1.1735	4.3512	0.2124
15	70	12.9049	11.7655	1.1394	4.3512	0.2075
16	75	12.8699	11.7655	1.1044	4.3512	0.2024
17	80	12.8336	11.7655	1.0681	4.3512	0.1971
18	85	12.7981	11.7655	1.0326	4.3512	0.1918
19	90	12.7634	11.7655	0.9979	4.3512	0.1866
20	95	12.7282	11.7655	0.9627	4.3512	0.1812
21	100	12.6929	11.7655	0.9274	4.3512	0.1757
22	110	12.6217	11.7655	0.8562	4.3512	0.1644
23	120	12.5487	11.7655	0.7832	4.3512	0.1525

Table 4.15 Measured Porosity Data over Time for Sample C3_C

No.	Time (min)	Saturated Weight (g)	Dry Weight (g)	Pore V (cm ³)	Grain V (cm ³)	Porosity
1	0	19.5436	17.4293	2.1143	6.4458	0.2470
2	5	19.5123	17.4293	2.0830	6.4458	0.2442
3	10	19.4816	17.4293	2.0523	6.4458	0.2415
4	15	19.4512	17.4293	2.0219	6.4458	0.2388
5	20	19.4211	17.4293	1.9918	6.4458	0.2361
6	25	19.3907	17.4293	1.9614	6.4458	0.2333
7	30	19.3597	17.4293	1.9304	6.4458	0.2305
8	35	19.3281	17.4293	1.8988	6.4458	0.2275
9	40	19.2965	17.4293	1.8672	6.4458	0.2246
10	45	19.2647	17.4293	1.8354	6.4458	0.2216
11	50	19.2337	17.4293	1.8044	6.4458	0.2187
12	55	19.2011	17.4293	1.7718	6.4458	0.2156
13	60	19.1684	17.4293	1.7391	6.4458	0.2125
14	65	19.1426	17.4293	1.7133	6.4458	0.2100
15	70	19.1139	17.4293	1.6846	6.4458	0.2072
16	75	19.0852	17.4293	1.6559	6.4458	0.2044
17	80	19.0554	17.4293	1.6261	6.4458	0.2015
18	85	19.0249	17.4293	1.5956	6.4458	0.1984
19	90	18.9936	17.4293	1.5643	6.4458	0.1953
20	95	18.9615	17.4293	1.5322	6.4458	0.1921
21	100	18.9289	17.4293	1.4996	6.4458	0.1887
22	110	18.8668	17.4293	1.4375	6.4458	0.1823
23	120	18.8058	17.4293	1.3765	6.4458	0.1760

Table 4.16 Measured Porosity Data over Time for Sample C3_D

No.	Time (min)	Saturated Weight (g)	Dry Weight (g)	Pore V (cm ³)	Grain V (cm ³)	Porosity
1	0	17.7649	15.9754	1.7895	5.9081	0.2325
2	5	17.7405	15.9754	1.7651	5.9081	0.2300
3	10	17.7187	15.9754	1.7433	5.9081	0.2278
4	15	17.6960	15.9754	1.7206	5.9081	0.2255
5	20	17.6729	15.9754	1.6975	5.9081	0.2232
6	25	17.6495	15.9754	1.6741	5.9081	0.2208
7	30	17.6257	15.9754	1.6503	5.9081	0.2183
8	35	17.6017	15.9754	1.6263	5.9081	0.2158
9	40	17.5779	15.9754	1.6025	5.9081	0.2134
10	45	17.5537	15.9754	1.5783	5.9081	0.2108
11	50	17.5286	15.9754	1.5532	5.9081	0.2082
12	55	17.5025	15.9754	1.5271	5.9081	0.2054
13	60	17.4767	15.9754	1.5013	5.9081	0.2026
14	65	17.4499	15.9754	1.4745	5.9081	0.1997
15	70	17.4231	15.9754	1.4477	5.9081	0.1968
16	75	17.3965	15.9754	1.4211	5.9081	0.1939
17	80	17.3668	15.9754	1.3914	5.9081	0.1906
18	85	17.3386	15.9754	1.3632	5.9081	0.1875
19	90	17.3103	15.9754	1.3349	5.9081	0.1843
20	95	17.2828	15.9754	1.3074	5.9081	0.1812
21	100	17.2561	15.9754	1.2807	5.9081	0.1782
22	110	17.2007	15.9754	1.2253	5.9081	0.1718
23	120	17.1465	15.9754	1.1711	5.9081	0.1654

4.4 Analysis on Porosity Measured from Cuttings

According to the tables presented in the last section, we found that the saturated weight of cutting samples decreases with time. The main reason is that the amount of water between cuttings decreases with time due to capillary pressure and evaporation of the liquid. Therefore, the value of porosity from each cutting samples is going to decrease with time.

In order to visually present the porosity results determined from core plugs and the corresponding artificial cuttings with various mesh sizes, we plot these data on the same figure for each core sample. Therefore, Figure 4.1 to 4.3 are generated to illustrate the relationship between calculated porosity from cuttings in four sizes and desaturation time as well as the reference porosity data from core plug samples C1, C2 and C3, respectively.

Figure 4.1 Measured porosity data over desaturation time for core #C1 ($k=47$ mD)

Figure 4.2 Measured porosity data over desaturation time for core #C2 (k=82 mD)

Figure 4.3 Measured porosity data over desaturation time for core #C3 (k=192 mD)

Figure 4.1 to 4.3 consistently indicate that at the beginning of desaturation process, the porosity data determined from all of cutting samples are overestimated compared with the reference data. In the meantime, there is a relationship between the error difference and the size of cuttings. The specific error difference of porosity for each cutting samples are shown in Table 4.17. For example, sample C3_A with diameters varying between 0.425 mm and 0.85 mm shows a deviation of 37.44%. By contrast, sample C3_D of which size is between 2.8 mm and 4.0 mm presents a lower error difference of 13.64%. As a whole, the larger size sample shows a relative small error, whereas cuttings with the smallest size cause the maximum error.

Table 4.17 Initial desaturation process of porosity deviation for all cutting samples

Sample Name	Core Porosity	Size A		Size B		Size C		Size D	
		ϕ_{t0}	$\Delta\phi$	ϕ_{t0}	$\Delta\phi$	ϕ_{t0}	$\Delta\phi$	ϕ_{t0}	$\Delta\phi$
C1	0.1909	0.2680	40.37%	0.2385	24.91%	0.2285	19.70%	0.2151	12.65%
C2	0.1874	0.2434	29.90%	0.2339	24.84%	0.2275	21.44%	0.2079	10.97%
C3	0.2046	0.2812	37.44%	0.2732	33.54%	0.2470	20.74%	0.2325	13.64%

From an overall perspective, in a certain time, the value of porosity from smaller size cuttings changes relatively greatly compare with that from larger size cuttings. In other words, results measured from cuttings with small variational amplitude are more stable and reliable. In addition, Figure 4.1 and 4.2 show a rule that the four cutting curves are very compact in a certain range. But the curves presented in Figure 4.3 do not follow such rule. Permeability may be one of the factors that cause such inconsistent tendency. Other reasons include experimental error and influence of the changing conditions, such as temperature, humidity.

According to these three figures, we can find an exact time for each sample of which the corresponding measured porosity is the accurate one that we need. If the time is shorter than necessary, extra amount of water remains between cuttings therefore the weight of saturated cuttings will be larger than necessary which makes the porosity overestimate. A longer time than necessary gives rise to the loss of the saturating fluids present in the pores of which the volume will smaller than the pore

volume itself. This situation leads to an underestimation of the porosity. Based on the above analysis and the information shown in the figures, we decide to choose 60 minutes as the optimum time for measuring porosity for further analysis.

Base on the porosity data obtained at the desaturation time of one hour, the summary of the measurement results for all samples is presented in Table 4.18. In addition, these results have been plotted in Figures 4.4 to 4.6.

Table 4.18 Porosity deviation for all samples

Sample Name	Core Porosity	Size A		Size B		Size C		Size D	
		ϕ	$\Delta\phi$	ϕ	$\Delta\phi$	ϕ	$\Delta\phi$	ϕ	$\Delta\phi$
C1	0.1909	0.1777	6.93%	0.1841	3.55%	0.1807	5.36%	0.1812	5.11%
C2	0.1874	0.1646	12.16%	0.1731	7.59%	0.1778	5.11%	0.1810	3.38%
C3	0.2046	0.1879	8.15%	0.2174	6.26%	0.2125	3.87%	0.2026	0.95%

Figure 4.4 Porosity measurement results for core #C1 (k=47 mD)

Figure 4.5 Porosity measurement results for core #C2 (k=82 mD)

Figure 4.6 Porosity measurement results for core #C3 (k=192 mD)

Based on porosity deviation data comparison shown in Table 4.17, or from Figures 4.3 to 4.6, we can find some trend. The porosity estimated from cuttings has a relationship with the size of the cuttings. A relative lower value of porosity is determined from the smallest cuttings size A which diameter ranges from 0.425 mm to 0.85 mm, and measurement on such size leads to the maximum error because it owns the largest deviation data. When a larger size is used, the measured porosity increases and size D, equivalent to diameters between 2.8 mm and 4.0 mm presents the best result. The data generated from the largest size D is the closest to the porosity measured from cores with minimum error.

Due to the core samples we used have different permeabilities, this factor may influence the porosity results from cuttings. We need to study the porosity data measured from the same sizes of cuttings that are crushed from the three core samples respectively. Through comparing with the reference porosity data, we can locate the exact time which corresponds to the accurate results for each cutting samples.

Figure 4.7 Porosity data measured from cuttings size C

Figure 4.8 Porosity data measured from cuttings size D

Table 4.19 Influence of permeability on optimum time measuring porosity of cuttings

No.	Core Sample	k (mD)	Optimum time, min	
			Size C	Size D
1	C1	47	48	43
2	C2	82	50	47
3	C3	192	75	55

According to the previous analysis, we know that the porosity data generated from larger size cuttings are more stable and reliable. So the results of cuttings with size C (2.0-2.8 mm) and D (2.8-4.0 mm) are selected for analysis which have been plotted in Figure 4.7 to 4.7. From these figures, the optimum time of cuttings, which from three different core samples, corresponding to the accurate porosity values can be obtained (Table 4.19). It shows that it takes a little longer time to get the precise results for samples with larger permeability. Due to the limitation of the amount of test samples, we could not clearly found the specific relationship between permeability and the optimum time for measuring porosity. For further analysis of the influence of

permeability on the results, plenty of samples with similar porosity values but with different permeabilities should be applied such a method.

4.5 Applicability of the Method on the Field

Through the experimental study and results analysis, the method of measuring porosity from cuttings employed in this project is available for a field application. Compared to the existing approaches, the main advantage of such a method is a direct evaluation of porosity with a simple, fast, and accurate measurement. Drill cuttings are easy to collect from shakers during a drilling project. We can estimate the density of samples by lithology analysis on the cuttings. Then following the measurement procedures, the porosity data can be obtained from drill cuttings. According to the current research, such a method applies only to cuttings that are from conventional reservoirs.

CHAPTER V

DISCUSSIONS AND CONCLUSIONS

In this thesis project, the methods applied for porosity and permeability measurements on drill cuttings have been reviewed firstly. Then we put emphasis on determining porosity from cuttings through experimental method. By referring to the method proposed by IFP and making some improvements, we successfully achieved the purpose of this project. As a method that is able to measure the porosity directly from cuttings, it does not require specific conditions, it is easy to operate and it is economical. Due to its simplicity and its consistency, this method could be employed on the field to provide a fast evaluation of the reservoir porosity.

Based on the analysis of porosity data estimated from artificial cuttings with various sizes compared with the reference value measured from core samples, we can draw the following conclusions:

- It is reasonable and realizable to estimate the porosity from cuttings by using the proposed measurement method. Such method has been evaluated on the sizes of cuttings down to 0.425 mm.
- At the beginning of the desaturation process, the evaluated data for all cutting sizes are larger than core porosity, or overestimated. We decided to use one hour as the optimum time for measuring porosity.
- The generated results have close relationship with the size of cuttings. For cuttings with larger size, the measured porosity ranges smaller over time compared with that from cuttings of smaller size. It means that the result obtained from largest size cuttings is more reliable and accurate.
- Results generated from cuttings with largest diameter (2.8-4.0 mm) show the minimum error difference, and the deviation is increased with the decrease of size.

- Analyzing the results from cuttings with same size but with different permeabilities shows that such parameter is a factor that influences the accuracy of the applied measurement approach.

CHAPTER VI

RECOMMENDATIONS

The following recommendations can be proposed out of this study for future work:

- Evaluate the porosity measurement method adopted in this project on the cuttings with different lithology and characteristics.
- There is still room for improvement on removing the interstitial liquid from cuttings and better preventing extra liquid from evaporation during the desaturation process.
- Permeability should be an important factor that affects the measured results. Through extra experiments on cutting samples with various permeability values, some rules or relationships which can be used for correction of porosity results may be revealed.
- Field tests should be conducted to further evaluate the proposed method: reproduce the measurement procedures on test samples of core plugs and drill cuttings which are from coring and mud logging respectively.
- For drill cuttings, measuring porosity is a part of a larger project devoted to the petrophysical characterization of a reservoir: it is valuable to devise more excellent approach of extracting other parameters like permeability, residual saturation and capillary pressure.

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