Characterization of the Pore Structure Heterogeneities in Heterogeneous Reservoirs Using CRAI Porosimetry

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Abstract

This paper elucidates the pore level physics of gas invasion in heterogeneous porous media when a slug of air is injected at constant rate. The porous medium is saturated with a wetting liquid prior to gas injection. When the rate of gas injection is very low and buoyancy forces are minimized in horizontal displacements, the magnitude of capillary pressures at the pore scale determines the pathways selected by the invading gas. As the gas invades a relatively large pore (such as a vug - of mm size pores in carbonate rocks), the gas pressure registered near the face of injection drops suddenly and then builds up again to invade the largest pore throat connecting it to adjacent pores. Constant rate air injection (CRAI) by forcing a known slug of air volume in a porous medium with heterogeneities and monitoring the pressure at the face of injection enables the determination of the volume and size distribution of macroscopic heterogeneities. The heterogeneities were vugs of size greater than 1mm^3 or were regions of high permeability surrounded by pore matrix of lower permeability. Flow visualization results obtained by conducting these experiments in sintered glass bead models with heterogeneities validated the rationale of this method that offers an inexpensive way for characterizing the pore structure of heterogeneous porous media. Results of vug size characterization are in very good agreement with the actual vug size made artificially in micromodels. The CRAI porosimetry has applications for routine core analysis for vugs greater than 1mm^3 in porous media that become accessible by air during the constant rate injection.

1. Introduction

More than 50% of the world's hydrocarbon reserves are in carbonate formations. Estimating petrophysical properties from X-ray CT scanning and NMR measurements in carbonate rocks has always been a bigger challenge than in sandstone formations. Carbonates are characterized by different types of porosity and complex pore-size distributions [1-2]. The characterization of pore structure with large scale heterogeneities in the 1 mm to 1000 mm size range (common sizes of vugs in vuggy carbonates) has been advanced using X-ray CT scanning and MRI imaging, however these are very expensive research tools with limited applicability for routine core analysis [1-2].

In our research, we have advanced the use of constant rate air injection porosimetry (CRAI) to detect pore space accessed by the nonwetting phase along the gas breakthrough pathways characterized by the continuum of large pore throats interconnecting large pore bodies [3]. Due to the large pore coordination number and size of vugs, a relatively large fraction of vugs is accessed by the invading non-wetting phase (air). If a low permeability barrier is employed at the exit end of a sample, the accessibility of vugs by air invasion can be carried out to much higher capillary pressure values where all of the vugs become accessible. The objective of this research is to develop a simple method to characterize the vugs and large permeability region surrounded by smaller permeability regions which are common features of heterogeneous porous samples. This will enable the development of better pore structure models for vuggy carbonates.

2. Experimental Aspects

A constant rate air injection (CRAI) porosimeter was designed for determination of vug sizes in heterogeneous porous media using an apparatus shown in Figure 1. The objective for CRAI porosimetry is to determine the volume of vugs and large scale heterogeneities invaded by a nonwetting phase in a porous sample. The principle of this porosimeter is the injection of a slug of air in a tube (that is attached to the inlet of the porous medium tested) at constant rate using a syringe pump filled with a liquid (water). Relatively low flow rates (~ 0.1 mm^3/s up to 0.6mm^3/s) were used using an ISCO syringe pump. Water in the pump pushes a slug of air in a tube and the front of the slug is displacing water from the porous medium as shown in Figure 1. As the gas phase invades a vug, the pressure drops over a short time period due to gas expansion and then rises to penetrate the largest pore throat leading away from it. A 2 psi Validyne

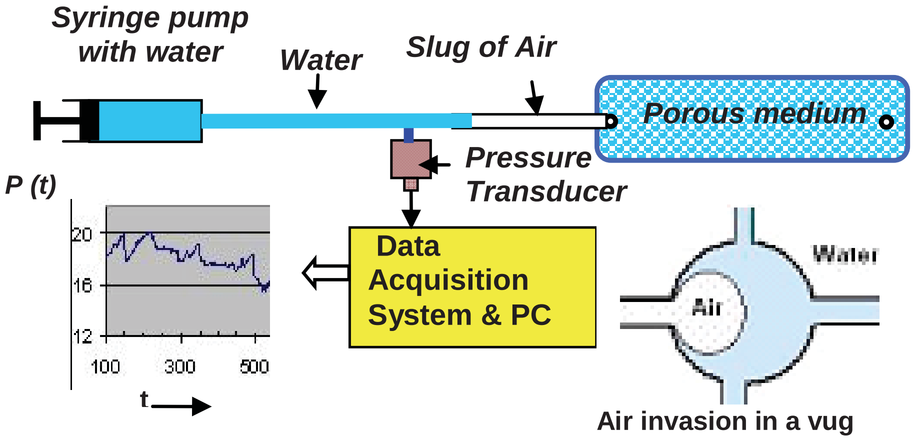


Figure 1. Experimental setup of the CRAI Porosimeter.

pressure transducer was employed to monitor the injection pressure, P (t), with time using the data acquisition system interfaced with the Labview software on a PC. An average value of 60 pressure measurements per second was recorded every second during the injection process to filter out random noise and plotted the P (t).

Several sintered glass beads micromodels with known pore structure heterogeneities were used. These models permit flow visualization of the displacement process. The micromodels used had a homogeneous pore matrix structure while vugs or regions of high permeability were surrounded by matrix pores. The porous media were fully saturated with water before injection of the slug of air into the model at constant rate. A pressure transducer enabled to record the pressure of the injecting fluid with a data acquisition and a microcomputer (PC) system. The inlet-fluid pressure was displayed on the PC monitor at any time during the injection process and the operator could keep notes of the time at which certain vug/heterogeneity is invaded by air by observing the model and the pressure trace P (t) on display. The Labview^{TM} software was used for collecting the P(t) data. It is very important that the slug of air in the tube be held horizontally to avoid any pressure changes caused by elevation differences of the injected water. It is also favorable to use a gas slug volume in the injection tube which is about the same as the volume of water displaced from the porous medium up to gas breakthrough, if the vugs invaded at the breakthrough pathways are of main interest.

At the start of an experiment, a known volume V_o of air slug is placed between the water in the tube delivered from the pump and the inlet of the water-saturated porous medium. Using the ideal gas law at any time during gas pressurization or gas expansion stages, the product $P(t)V(t) = P_o V_o$ applies for the slug of gas at any time. In the course of air invasion into a vug, the pressure trace characteristics are of three types:

a) Invasion by the snap-off mechanism, as seen with the signature of pressure trace shown by vugs 1 and 8 in Figure 2 respectively;

b) Fast invasion with no gas phase disconnection happening during the Haines jump, as shown by the signature of pressure trace for invasion in vug #7; and

c) Combination invasion that involves snap-off and direct invasion characteristics as shown by the pressure trace signature for invading vug #4 in Figure 2. The pressure drop is due to gas expansion and the lower capillary pressure in a vug pore space. Known the P(t) value and the rate of water injection Q to pressurize the slug of air, the volume of a vug, V_{vug} for direct invasion was found to be described by (see Figure 3):

$$V_{vug} = \Delta V + Q.(\Delta t_{Exp} + \Delta t_{Comp}) \tag{1}$$

where ΔV is calculated by the relation:

$$\Delta V = V_3 - V_1 = P_0 V_0 \left(\frac{1}{P_3} - \frac{1}{P_1}\right) \tag{2}$$

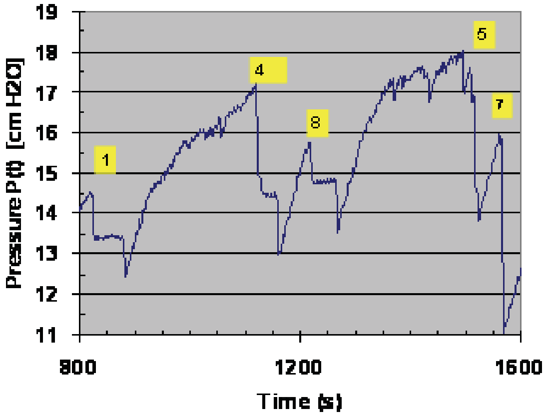


Figure 2. Pressure trace characteristics when invading vugs in model VN-2 at Q =1.6 ml/hr.

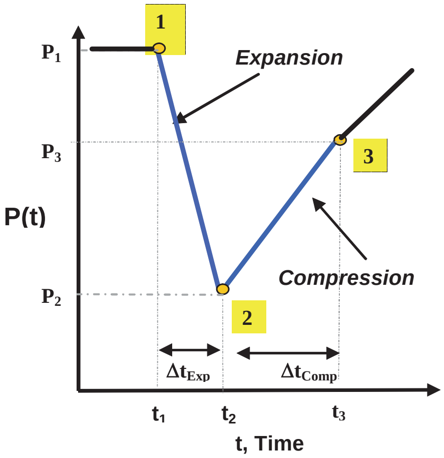


Figure 3. Simplified schematic of vug invasion pressure trace events.

Point 1 in Figure 3 indicates the entry pressure at time t_1 into a vug, point 2 indicates the minimum pressure attained at time t_2 when the liquid in the vug is displaced and point 3 indicates that the gas phase starts to penetrate into the adjacent matrix pores in the walls of a vug as the slope changes. When we have the gas invasion into a vug by the snap-off mechanism, the vug volume is approximated by:

$$V_{vug} = (V_2 - V_1) + Q.(\Delta t_{Exp}) \tag{3}$$

Using the characteristics of expansion stage, a dimensionless parameter can be defined in the form:

$$F_{so} = \frac{Q.\Delta t_{Exp}}{\Delta V_{Exp}} \tag{4}$$

where Q is the flow rate of injected fluid, Δt_{Exp} and ΔV_{Exp} are the characteristics of gas expansion stage (see Figure 3). F_{so} is an important parameter used for detecting the different types of invasion. For the experiments carried out using the VN-1 vuggy model, an 1800 mm^3 slug of gas was used and an injection flow-rate of 0.3 mm^3/s. The critical conditions for different type of invasion in this micromodel had as follows:

- Uncontrolled invasion or fast direct invasion *when* $F_{so} < 0.5$
- *Invasion by the* snap-off mechanism *when* $F_{so} > 1.5$.

When F_{so} was greater than 1.5, it was observed that snap-off is happening slower, and for F_{so} values greater than 8, it is an indication of very slow snap-off. The reason for using such a formulation is that when the invasion process is very fast, the characteristics of expansion alone would tend to under-estimate the vug size. The expansion part of gas invasion is instantaneous and not controlled by the flow rate of the injected fluid. Even if there was no flow of the injected fluid just at the time of gas invasion, the gas expansion stage would have happened. In fast invasion, the liquid in the vug keeps draining during the compression stage too. The reader should notice that if the pressure rises up to the invasion entry pressure (i.e., $P_1 = P_3$), the first term in Equation (1) is eliminated and the second term by itself represents the volume of vug. If $P_1=P_{3,}$ then the vug volume $V_{vug}= Q.(\Delta t_{Exp}+\Delta t_{Comp})$, which is the classical formulation for filling a vug with a certain flow-rate Q in a certain period of time $(\Delta t_{Exp}+\Delta t_{Comp})$ [4]. Most of the vugs invaded do not show the condition of $P_1 = P_3$ to materialize, as there is also matrix invasion during the compression period in the surface pores of a vug.

3. Porous Media Used in Experiments

Experiments were conducted in synthetic porous media having vugs of known size. Several micromodels were prepared by sintering glass beads between glass plates. Vugs were created by either drilling holes of known size or by placing carbonate particles of known sizes that are leached out by acids to create the vugs. Only some of the micromodels tested are shown in Figure 4. The volume of each of the vugs was determined from the optical cross-section area of the vug using image analysis and the known thickness of micromodel in models VN-1 and VN-2. In the case of irregular vugs in models VN-5 and VN-7, the bulk volume of individual particles leached away. (e.g. models VN-5, VN-7) was measured prior to sintering them along with glass beads. Model VN-7 had a mixture of vug and lenses of larger size beads (1400μm beads marked as M1, M2, etc.) embedded in a continuum of 400μm size glass beads as seen in the top view photo shown as plate D in Figure 4.

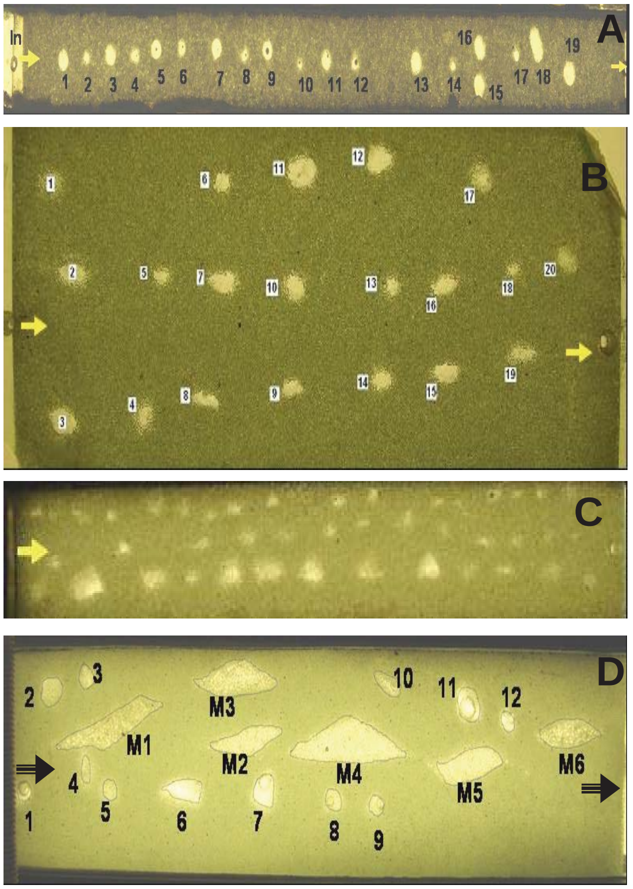
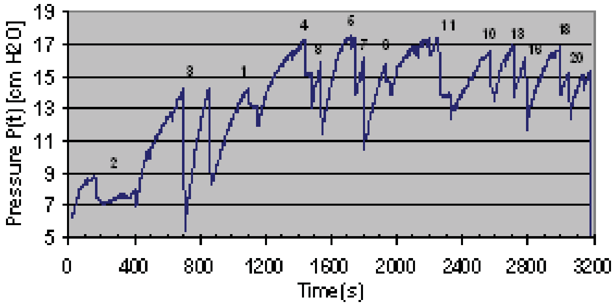


Figure 4. Photographs of some of the vuggy porosity micromodels. The vugs are indicated by the numbers 1, 2, 3, etc. Plate A is a picture of the model VN-1 with 19 vugs; Plate B is a picture of the model VN-2 with 20 vugs; Plate C is model VN-5 with 48 vugs created by leaching away carbonate particles of various sizes; Plate D is model VN-7 that contained 12 vugs and 6 lenses identified by letter M which are isolated regions of 1400 μm large particles surrounded by matrix of 300 μm particles that formed the continuum.

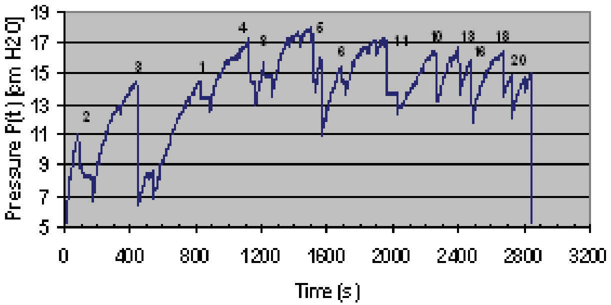
4. Results and Discussion

4a. Determination of vug sizes

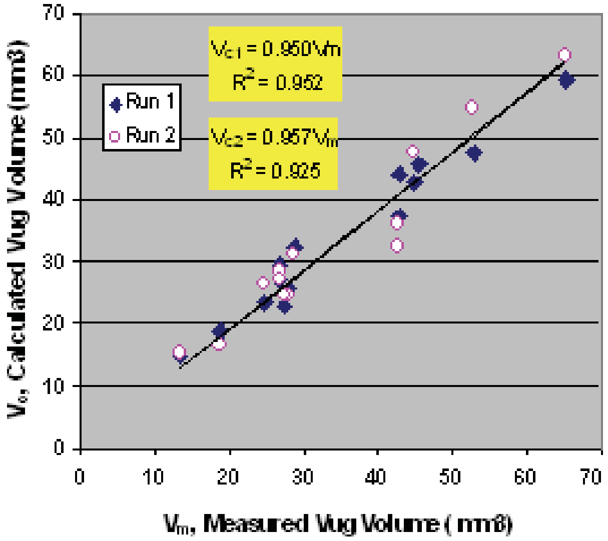
Typical pressure trace results obtained with model VN-2 are shown in Figures 5a and 5b for a slug of air with a volume of 4,200mm^3 displacing water. These figures also illustrate that the pressure trace details are repeatable if the sequence of pore invasion remains unchanged. Determination of vug size from the P(t) data and comparison with the measured sizes of vugs is also shown in Figure 5c. It is clear that very good agreement was found between the estimated and the actual sizes.



a) Pressure trace results for Run 1, Vt = 4,200 mm^3, Q = 1,800 m^3/hr



b) Pressure trace results for Run 2, Vt = 4,200 mm^3, Q = 1,600 m^3/hr



c) Vug size determined from the P(t) data and comparison with corresponding measurements

Figure 5. Repeatability of results of pressure trace experiments in micromodel VN-2 and plot of vug size from P(t) results versus vug size measured by image analysis.

A test was also performed with constant rate mercury injection (CRMI) porosimetry with a slug of mercury to displace the water in the porous medium. Comparison of the constant rate air injection porosimetry (CRAI) results with constant rate mercury injection (CRMI or APEX porosimetry [4]) was made using model VN-1 having 19 vugs. The slug of air displacing water and the slug of mercury displacing water were propagated at the same rate in two separate experiments, respectively. The calculated vug sizes by these two different methods are shown in Figure 6. The calculated vug sizes appear to be more accurate when the pressure trace obtained by CRAI is used compared to those obtained from the pressure trace results of CRMI. The vug sizes obtained by CRMI porosimetry using the rules of reference [4] were found to be much larger than the actual sizes in place. This is primarily caused by the global imbibition phenomena in the entire pore space invaded by the non-wetting fluid. This phenomenon is not as pronounced in air displacing a a wetting liquid.

4b. Determination of Vug Size Distribution

Model porous media with variable vug sizes in the range of 8 to 128 mm^3 were prepared by sintering irregular carbonate rock particles of known volume and placed apart in a continuum of 500µm glass beads as shown in plate C in Figure 4. This micromodel VN-5 was prepared for simulating porous media with isolated vugs. Micromodel VN-5 had 48 vugs of different sizes and were classified in interval shown in the histogram of Figure 7. The pressure trace results of CRAI obtained for model VN-5 were used to determine vug sizes. We identified also 48 features in the pressure trace of this model that had typical vug invasion signature. The size distribution of vugs detected in micromodel VN-5 was in very good agreement with the actual vug size distribution in the model. This test confirmed that the CRAI porosimetry can be used for determination of vug size distributions in heterogeneous porous media. More tests are in progress in our laboratory using cores of vuggy carbonate rocks. So far samples with a pore volume less than 10 cm^3 can be tested using CRAI porosimetry.

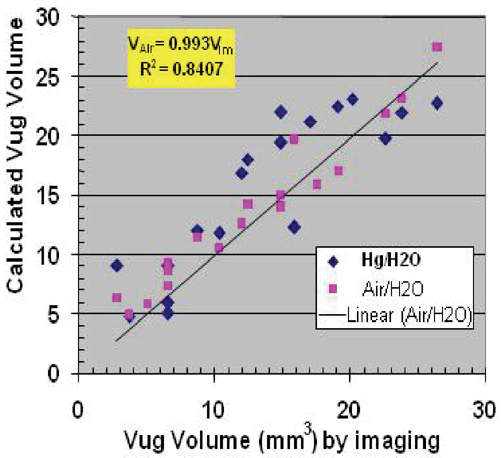


Figure 6. Vug size determination in model VN-1 from pressure trace data of CRAI and CRMI porosimetry.

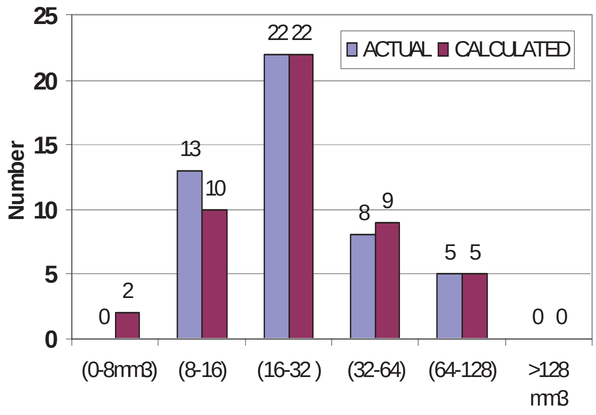


Figure 7. Comparison of calculated vug sizes to actual sizes.

4c. Determination of vugs and high permeability regions

For cases of heterogeneous media that have vugs and regions of high permeability whereby they do not percolate (see plate D for model VN-7 in Figure 4), the pressure trace of the CRAI experiments of a system like the structure of micromodel VN-7 shows to be similar to the vug only invasion signature in the pressure trace. Regions of high permeability are invaded by the gas phase much like gas is invading vugs. Therefore it is difficult to differentiate the pressure trace signature for gas invasion in vugs from that of gas invasion in a region of high permeability (e.g. invasions in regions identified as M1, M2, etc. in Figure 4).

5. Conclusions

- Based on experimental evidence presented in this paper, the constant rate air injection porosimetry is a simple technique that can be adapted to detect the presence of vugs in porous media, as well as calculate the volume of vug sizes and/or clusters of high permeability in heterogeneous porous media like vuggy carbonates.
- Volumes of vugs greater than 1mm^3 can be determined accurately when accurate pressure transducers and low injection rates (i.e., less than $0.2\text{mm}^3/\text{s}$) are used.

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Author Biographies

Dr. Ioannis Chatzis is a Visiting Distinguished Professor in the Department of Petroleum Engineering at the Petroleum Institute. He is sabbatical leave of absence for the entire year of 2008 from the University of Waterloo, Canada, where he is Professor of Chemical Engineering. He received all his degrees from the University of Waterloo (BASc 1974, MASc 1976, and Ph.D. 1980), which he joined in 1982 as a faculty member. He has supervised over 14 Ph.D. students and 24 Master's degree students. About half of his former Ph.D. students are now employed in academia, and the rest in research institutions. He teaches courses in Transport and Interfacial Phenomena, Reservoir Engineering, Flow in Porous Media, and Separation Processes. He is well known internationally for his research contributions on capillary and transport phenomena in porous media, with applications to pore structure characterization and novel EOR processes for the *in-situ* recovery of heavy oil from tar sand deposits. He has published extensively and has received the "Darcy" Technical Achievement Award of the International Society of Core Analysts in 2006 for his lifetime contributions to the field of Core Analysis. He is an inventor with three patents and co-author of a textbook titled "Introduction to Equilibrium Stage Separations".

Mr. Nima Resaei is a Ph.D. candidate in the Chemical Engineering Department, University of Waterloo. His research interests are in heavy oil recovery using solvent aided and thermal processes, and he has authored several papers. He is a student member of SPE.