A NEW METHOD FOR CHARACTERIZING THE PORE STRUCTURE HETEROGENEITIES IN CARBONATE CORE SAMPLES

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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 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 accessed by a gas during constant rate gas injection.

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 1mm to 1000mm 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.

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 Fig.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 Fig. 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 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™ 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 favourable to use a gas slug volume in the injection tube which is about the same as the volume of water displaced from the porous

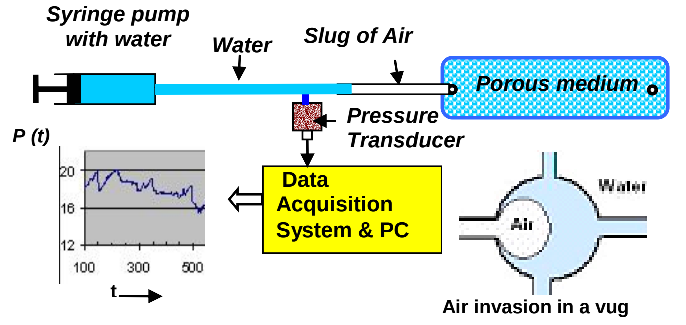

Fig. 1: Experimental setup of the CRAI Porosimeter

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 $P(t)V(t) = P_oV_o$ 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 Fig.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} when direct invasion occurs was found to be described by the relation (see Fig.3):

$V_{vug} = \Delta V + Q.(\Delta t_{Exp} + \Delta t_{Comp})$ (Eq.1) ,where ΔV is calculated by the relation:

$\Delta V = V_3 - V_1 = P_0V_0\left(\frac{1}{P_3} - \frac{1}{P_1}\right)$ (Eq.2). Point 1 in Fig.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:

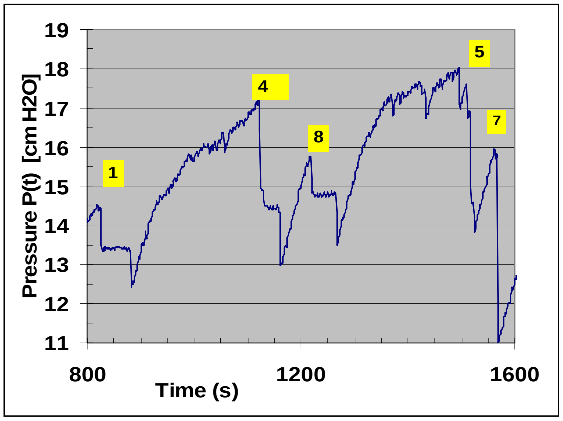

Fig. 2: Pressure trace characteristics when invading vugs in model VN-2 at Q =1.6 ml/hr

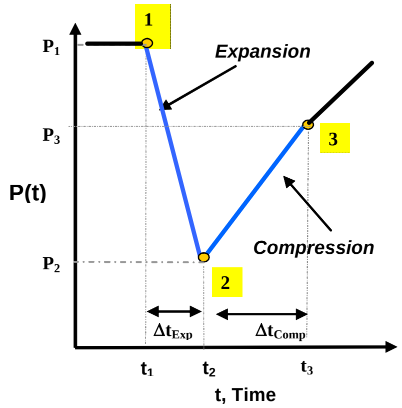

Fig. 3: Simplified schematic of vug invasion pressure trace events:

$V_{vug} = (V_2 - V_1) + Q.(\Delta t_{Exp})$ Eq. (3). Using the characteristics of expansion stage, a dimensionless parameter can be defined in the form $F_{so} = \frac{Q.\Delta t_{Exp}}{\Delta V_{Exp}}$ Eq.(4), where *Q* is the flow rate of injecting fluid, Δt_{Exp} and ΔV_{Exp} are the characteristics of expansion stage (see Fig. 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 w*hen* $F_{so} < 0.5$
- *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 Eq. (1) is eliminated and only the second term represents the volume of the vug. If $P_1=P_3$, then $V_{vug}=Q.(\Delta t_{Exp}+\Delta t_{Comp})$, 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.

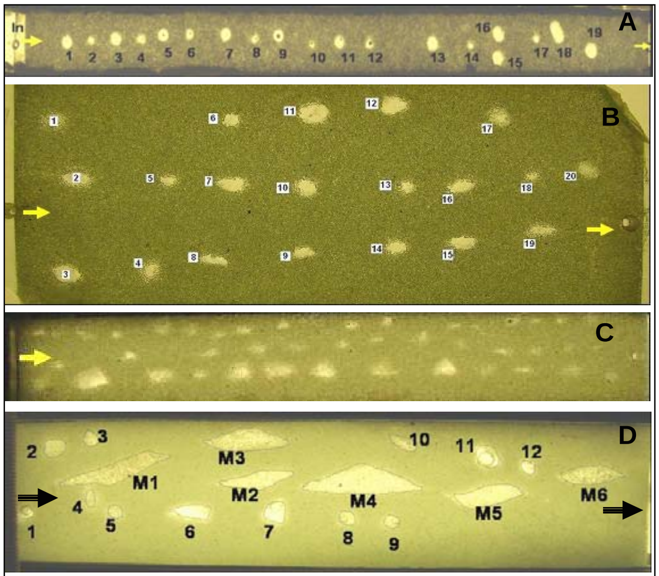

Fig.4: Photographs of some of the vuggy porosity micromodels used. The vugs are indicated by numbers 1, 2, 3, etc. A) picture of model VN-1 : B) model VN-2 with 20 vugs; C) model VN-5 with 48 vugs created by leaching particles; D) model VN-7 with 12 vugs and 6 lenses of large particles of glass beads (M 1400μm) in a matrix of 400μm

POROUS MEDIA USED: 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 Fig.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 top view photo D in Fig. 4.

RESULTS & DISCUSSION

a. Determination of vug sizes: Typical pressure trace results obtained with model VN-2 are shown in Fig. 5 for a slug of air with a volume of 4200mm^3 displacing water. This figure also illustrates 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 Fig. 5. Very good agreement was found.

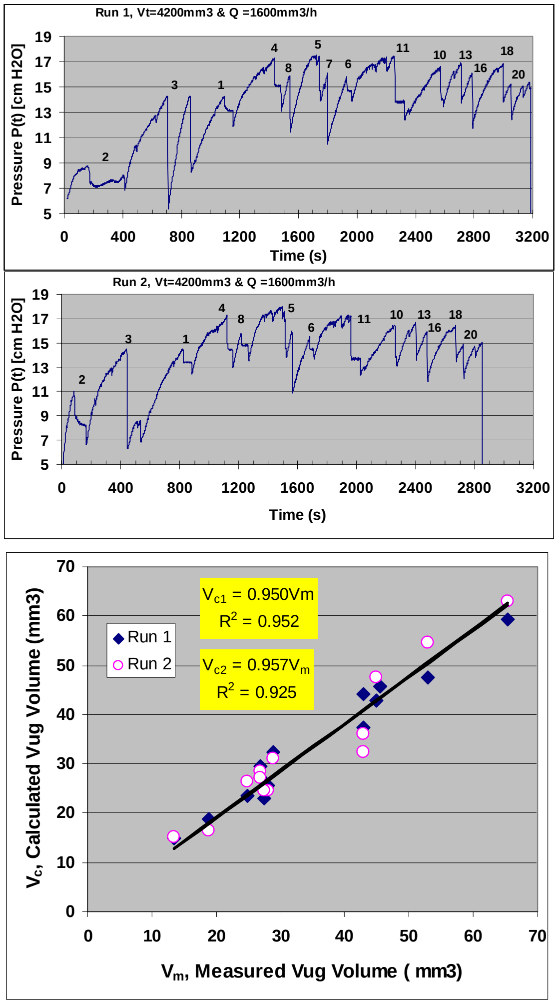

Fig.5: Repeatability of results of pressure trace experiments in VN-2 and plot of vug size from P(t) results versus vug size measured by image analysis.

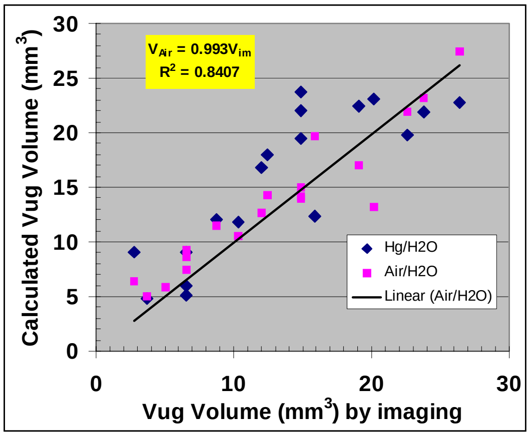

Fig. 6: Vug size determination in model VN-1 from P(t) by CRAI and CRMI

Comparison of constant rate air injection porosimetry (CRAI) with constant rate mercury injection (CRMI or APEX pososimetry [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 Fig. 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 size of vugs in CRMI when determined according to the rules of reference [4] were found to be larger than the actual sizes in place, primarily due to global imbibition phenomena [4].

b. 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 placed apart in a continuum of 400 μm glass beads as shown in plate C in Fig. 4 for micromodel VN-5, thus simulating porous media with isolated vugs. Micromodel VN-5 had 48 vugs of different sizes and the vugs were classified in interval shown in the histogram of Fig. 7. The pressure trace results of CRAI in model VN-5 was used to determine vug sizes. We identified also 48 features in the pressure trace of this model that are typical of vug invasion signature.

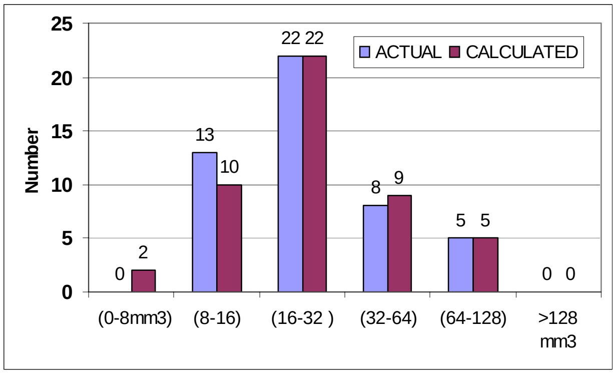

Fig.7: Number frequency of actual and calculated vug sizes using CRAI in micromodel VN-5

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.

c. Determination of vugs & clusters of high permeability regions: In 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 Fig. 4), the pressure traces of CRAI experiments of such system like micromodel VN-7 structure show to be similar to 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 gas invasion in vugs from that of gas invasion in a cluster of high permeability region (e.g. regions identified as M1, M2, etc. in Figure 4).

CONCLUSION

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 0.2mm^3/s) are used.

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